U.S. DEPARTMENT OF COMMERCE
National Technical Information Service
PB80-114283

Municipal Solid Waste: Resource Recovery. Proceedings of the Fifth Annual Research Symposium Held at Orlando, Florida on March 26, 27 and 28, 1979

University of Central Florida, Orlando

Prepared for

Municipal Environmental Research Lab, Cincinnati, OH

Aug 79

United States
Environmental Protection
Agency

Municipal Environmental Research
Laboratory
Cincinnati OH 45268

EPA-600/9-79-023b
August 1979

Research and Development

PB80-114283

Municipal Solid Waste: Resource Recovery

Proceedings of the Fifth Annual Research Symposium

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U. S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

RESEARCH REPORTING SERIES

Research reports of the Office of Research and Development, U.S. Environmental Protection Agency, have been grouped into nine series. These nine broad categories were established to facilitate further development and application of environmental technology. Elimination of traditional grouping was consciously planned to foster technology transfer and a maximum interface in related fields. The nine series are:

1. Environmental Health Effects Research
2. Environmental Protection Technology
3. Ecological Research
4. Environmental Monitoring
5. Socioeconomic Environmental Studies
6. Scientific and Technical Assessment Reports (STAR)
7. Interagency Energy-Environment Research and Development
8. "Special" Reports
9. Miscellaneous Reports

This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA-600/9-79-023b	2.	3. RECIPIENT'S ACCESSION NO. PB80-114283
4. TITLE AND SUBTITLE MUNICIPAL SOLID WASTE: RESOURCE RECOVERY Proceedings of the Fifth Annual Research Symposium		5. REPORT DATE August 1979 (Issuing Date) 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) John Larson, Editor		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS University of Central Florida Box 25000 Orlando, Florida 32816		10. PROGRAM ELEMENT NO. 1DC818 11. CONTRACT/GRANT NO. 806198
12. SPONSORING AGENCY NAME AND ADDRESS Municipal Environmental Research Laboratory--Cin., OH Office of Research and Development U.S. Environmental Protection Agency Cincinnati, Ohio 45268		13. TYPE OF REPORT AND PERIOD COVERED Symposium March 26-28, 1979 14. SPONSORING AGENCY CODE EPA-600/14

15. SUPPLEMENTARY NOTES

See also Municipal Solid Waste: Land Disposal, EPA-600/9-79-023a
Project Officer: Robert E. Landreth (513) 684-7748

16. ABSTRACT

The fifth SHWRD research symposium on land disposal and resource recovery of municipal solid waste was held at Orlando, Florida on March 26, 27, and 28, 1979. The purposes of the symposium were (1) to provide a forum for a state-of-the-art review and discussion of ongoing and recently-completed research projects dealing with the management of solid wastes; (2) to bring together people concerned with municipal solid waste management who can benefit from an exchange of ideas and information; and (3) to provide an arena for the peer review of SHWRD's overall research approach. These proceedings are a compilation of the papers presented by the symposium speakers. They are arranged in order of presentation. Volume I, land disposal, covered four primary technical areas: Pollutant Identification, Environmental Assessment, Control Technology, and Pollutant Transport. Volume II, Resource Recovery, covered five primary technical areas: Evaluation of Equipment, Unit Operations, and Processes; Economics and Impediments; Systems Analysis and Special Studies; Utilization of Recovered Materials; and Environmental Impacts of Resource Recovery.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Comminution	Refuse Maintenance	5A
Waste Treatment	Shredder Design	5B
Size Reduction	Waste-as-fuels	13B
Marketing	Resource Recovery	
Prices	Secondary Materials	
Energy		

18. DISTRIBUTION STATEMENT RELEASE TO PUBLIC	19. SECURITY CLASS *(This Report)* UNCLASSIFIED	21. NO. OF PAGES 424
	20. SECURITY CLASS *(This page)* UNCLASSIFIED	22. PRICE A18-A01

EPA Form 2220-1 (9-73)

☆ U.S. GOVERNMENT PRINTING OFFICE 1979 -657-060/5439

EPA-600/9-79-023b
August 1979

MUNICIPAL SOLID WASTE: RESOURCE RECOVERY

Proceedings of the Fifth Annual Research Symposium
at Orlando, Florida, March 26, 27, and 28, 1979
Cosponsored by the University of Central Florida
and the Solid and Hazardous Waste Research Division
U.S. Environmental Protection Agency

Edited by:

Martin P. Wanielista
and
James S. Taylor
Department of Civil Engineering and Environmental Sciences
University of Central Florida
Orlando, Florida 32816

Grant No. 806198

Project Officers:

Stephen C. James
Robert E. Landreth
Solid and Hazardous Waste Research Division
Municipal Environmental Research Laboratory
Cincinnati, Ohio 45268

MUNICIPAL ENVIRONMENTAL RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
CINCINNATI, OHIO 45268

DISCLAIMER

These Proceedings have been reviewed by the U.S. Environmental Protection Agency and approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of the U.S. Environmental Protection Agency, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

FOREWORD

The Environmental Protection Agency was created because of increasing public and governmental concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimony to the deterioration of our natural environment. The complexity of the environment and the interplay between its components require a concentrated and integrated attack on the problem.

Research and development is the first necessary step in problem solution; it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems to prevent, treat, and manage wastewater and the solid and hazardous waste pollutant discharges from municipal and community sources; to preserve and treat public drinking water supplies; and to minimize the adverse economic, social, health and aesthetic effects of pollution. This publication is one of the products of that research -- a vital communications link between the researcher and the user community.

The Proceedings present research aimed at minimizing the impact of land disposal of solid and hazardous wastes. Solutions to specific probelms are suggested.

Francis T. Mayo
Director
Municipal Environmental Research Laboratory

PREFACE

These Proceedings are intended to disseminate up-to-date information on extramural research projects dealing with the disposal of solid and hazardous wastes. These projects are funded by the Solid and Hazardous Waste Research Division (SHWRD) of the U.S. Environmental Protection Agency, Municipal Environmental Research Laboratory in Cincinnati, Ohio. Selected papers from work of other organizations were included in the symposium to identify closely-related work not included in the SHWRD program.

The papers in these Proceedings are arranged as they were presented at the symposium. There were two concurrent programs, one primarily for land disposal and the other primarily for resource recovery. Each program had multiple sessions. There was an introductory session. Each of the five sessions includes papers dealing with major areas of interest for those involved in solid and hazardous waste management and research. Each program, land disposal and resource recovery, is printed in a separate volume.

The papers are printed here basically as received from the symposium authors. They do not necessarily reflect the policies and opinions of the U.S. Environmental Protection Agency or the University of Central Florida. Hopefully, these Proceedings will prove useful and beneficial to the scientific and engineering community as a current reference on land disposal and resource recovery.

ABSTRACT

The Fifth Solid and Hazardous Waste Research Division (SHWRD) research symposium on Municipal Solid Waste: Land Disposal and Resource Recovery was held at the Marriott Inn in Orlando, Florida on March 26, 27, and 28, 1979. As in previous symposiums, the purpose was similar. State-of-the-art review and discussion of ongoing and recently completed research projects were primary objectives. In addition, the symposium attracted individuals with a variety of educational backgrounds and jobs who benefited from an exchange of ideas and information. The symposium had a dual theme -- Gas and Leachate in Landfills and Resource Recovery. The Proceedings are published in two volumes to correspond with the dual theme. The proceedings are essentially the papers presented by symposium speakers. The papers are arranged in the order of presentation. For this volume, the sessions presented are related to research on resource recovery and are: (1) Introduction, (2) Mechanical Unit Processes, (3) Chemical Processes, (4) Economic Research Related to Solid Waste Management, (5) System Studies and Special Projects, (6) Utilization of Recovery Materials, (7) Environmental Impacts of Resource Recovery, (8) Bioconversion.

This report was submitted in fulfillment of Research Grant No. 806198 by the University of Central Florida under the sponsorship of the U.S. Environmental Protection Agency. This report covers the period from October 1978 to July 1979, and work was completed as of July 1979.

CONTENTS

Page

Disclaimer ii

Foreword iii

Preface iv

Abstract v

Contents vii

SESSION I: MECHANICAL UNIT PROCESSES

Pilot Scale Processing Equipment Evaluation for Resource Recovery
Harvey Alter, National Center for Resource Recovery, Inc. 40

Mid-Shakedown Evaluation of a Demonstration Resource Recovery Facility
J. F. Bernheisel, National Center for Resource Recovery......................... 60

Research and Evaluation of Solid Waste Processing Equipment
David Bendersky and Bruce Simister, Midwest Research Institute 77

Evaluation and Performance of Hammermill Shredders used in Refuse Processing
G. M. Savage, G.R. Adiflett, L.F. Diaz and G.J. Trezek, Cal Recovery Systems, Inc. 86

SESSION II: CHEMICAL PROCESSES

Development of Continuous Acid Hydrolysis Process for the Utilization of Waste Cellulose

Preceding page blank

Walter Brenner, Barry Rugg, Robert Stanton, Peter Armstrong and Kuan-Ming Ang, New York University 99

Production of Methane from Acid Hydrolysates of Cellulose Wastes
V.R. Srinivason, Louisiana State University 114

Stabilization and Characterization of Pyrolytic Oils
Malcolm B. Polk and Metha Phingbodhipakkiya, Atlanta University 118

Pyrolytic Oils from Agricultural and Forestry Residues and Municipal Solid Waste
J. A. Knight, Georgia Institute of Technology 126

SESSION III: ECONOMIC RESEARCH RELATED TO SOLID WASTE MANAGEMENT

Some Empirical Evidence on the Effects of User Charges for Solid Waste Collection Services
Robert J. Anderson, MATHTECH, Inc. 130

The Desirability of Commodity Futures Trading in Scrap Materials
Roger C. Dower and Elizabeth H. Granitz, Environmental Law Institute 141

An Economic Analysis of Paper Recycling
Roger Bolton, Williams College 151

Economic and Institutional Impediments to Conservation and Recycling
Robert C. Anderson, Environmental Law Institute 170

SESSION IV: SYSTEMS STUDIES AND SPECIAL PROJECTS

Small-Scale and Low Technology Resource Recovery
Gary L. Mitchell and Charles W. Peterson, SCS Engineers 179

Compatibility of Source Separation and Mixed-Waste Processing for Resource Recovery
Harry H. Fielder and Belur N. Murthy, Gilbert & Associates, Inc. 197

Forecasts of the Quantity and Composition of Solid Waste
Ralph M. Doggett, International Research and Technology Corporation
Andrea L. Watson, Bechtel Corporation 220

SESSION V: RESEARCH ON RESOURCE RECOVERY

The Development of Testing and Analysis Procedures for Refuse-Derived Fuel
John Love, University of Missouri-Columbia
Carlton C. Wiles, U.S. Environmental Protection Agency 225

Calorific Value Determination of Refuse-Derived-Fuels by Large-Bomb Calorimetry
Duane R. Kirklin, Eugene S. Domalski and David J. Mitchell, National Bureau of Standards 233

SESSION VI: UTILIZATION OF RECOVERED MATERIALS

Technical, Economic and Market Evaluation on the use of Waste Glass in Structural Clay Brick Manufacture
Ashok K. Gupta, Ratheon Service Company
Laura A. Arozarena, U.S. Environmental Protection Agency 248

The Production and Use of Densified Refuse Derived Fuel
Carlton C. Wiles, U.S. Environmental Protection Agency 274

Status, Trends, and Impediments to Discarded Tire Collection and Resource Recovery
James F. Hudson, Patricia L. Deese and Douglas Funkhouser,
Urban Systems Research & Engineering, Inc. 293

Advanced Thermal and Chemical Concepts for Improved MSW Derived Products
N. L. Hecht and D. S. Duvall, University of Dayton
Research Institute 303

SESSION VII: ENVIRONMENTAL IMPACTS OF RESOURCE RECOVERY

Environmental Impact of Resource Recovery
Judith G. Gordon, MITRE Corporation 316

Environmental Assessments of Waste to Fuel Processes
H. M. Freeman, U.S. Environmental Protection Agency 329

The Occurrence of Lead in Municipal Solid Waste
David F. Lewis and Ada Salas, York Research Corporation 339

SESSION VIII: BIOCONVERSION

Start-Ups and Operation of the Landfill, Gas Treatment Plant at Mountain View
M. J. Blanchet, Pacific Gas and Electric Company 346

Anaerobic Digestion of Agricultural Residues - A Technology Assessment
Tom P. Abeles and David Elsworth, i e associates, inc.
John P. Genereaux, Genereaux Social Science Consultants 353

Gas Recovery from MSW - Sewage Sludge Anaerobic Digesters
Joseph T. Swartzbaugh, Catherine E. Jarvis and Ralph B. Smith,
Systems Technology Corporation 373

PROGRAMS IN LAND DISPOSAL AND RESOURCE RECOVERY AND CONSERVATION

John H. Skinner
Director, Land Disposal Division
Office of Solid Waste
U.S. Environmental Protection Agency
Washington, D.C.

ABSTRACT

This paper describes EPA's programs in land disposal and resource recovery and conservation. The programs are authorized by the Resource Conservation and Recovery Act (RCRA) of 1976, which also authorizes the hazardous waste programs carried out by the Agency. RCRA is implemented by EPA's Office of Solid Waste. The land disposal and resource recovery and conservation programs include:

1. development of regulations and guidelines,
2. technology demonstrations and evaluations,
3. studies and information development, and
4. technical and financial assistance.

The basic purpose and objectives of these activities are summarized and expected accomplishments and milestones for the next year are presented.

INTRODUCTION

Programs of the U.S. Environmental Protection Agency, Office of Solid Waste (OSW) are carried out under the authority of the Resource Conservation and Recovery Act of 1976 (RCRA). The basic objectives of this Act are to promote the application of improved solid waste management in order to protect public health and the environment and to conserve valuable material and energy resources. Based on the requirements and priorities in the Act, OSW has developed programs in these areas:

1. hazardous waste management,
2. land disposal, and
3. resource recovery and conservation.

Since the subjects of this Symposium are land disposal and resource recovery, this paper will focus only on those activities. First, specific projects on land disposal and resource recovery will be discussed, followed by a discussion of the technical and financial assistance available to help build State and local government programs.

LAND DISPOSAL

Land disposal activities can be grouped into two categories:

1. development of regulations and guidelines, and
2. technology demonstrations and technical information.

Regulations and Guidelines

The keystone to the disposal provisions of RCRA are the Criteria for Classification of Solid Waste Disposal Facilities (the Disposal Criteria) called for by Section 4004 of the Act. The Disposal Criteria will establish national standards for solid waste disposal by distinguishing facilities that pose no reasonable probability of adverse effects on health or the environment. Facilities not complying with these criteria are termed "open dumps" and are prohibited by the Act. The Disposal Criteria were published in proposed form in the Federal Register on February 6, 1978. Final promulgation is expected in mid-1979,

Section 4005 of RCRA requires EPA to publish an inventory of all disposal facilities in the United States that are open dumps, i.e. facilities that do not comply with the Disposal Criteria. Any facility found to be an open dump must be closed or upgraded according to a State-established compliance schedule. Financial assistance will be provided to State solid waste programs to evaluate facilities for purposes of the open dump inventory. A site classification manual is being developed which will provide a practical interpretation of the Disposal Criteria and will be useful to the States in evaluating facilities for purposes of the open dump inventory. Also another manual is being developed describing procedures and techniques for closing or upgrading open dumps.

RCRA calls for publication of the open-dump inventory one year after final promulgation of the Disposal Criteria. However, due to the large number of facilities to be evaluated and the complexity of such evaluations, the inventory will be published in annual installments. An arrangement has been made with the Bureau of Census to handle the data processing and actual inventory publication.

For the most part the Disposal Criteria do not specify particular technologies or operational approaches but instead establish performance levels as necessary to protect public health and the environment. This was done to allow different technologies and operations to be used as the local situation dictated and to provide opportunity for new and innovative approaches. However, RCRA does call upon EPA to provide guidance on technologies.

Section 1008 directs the Agency to develop and publish suggested guidelines that provide a technical and economic description of various solid waste management practices (including operating practices). One such guideline describing the practice of landfilling is under development at this time. This guideline will discuss design and operation of a landfill in order to protect public health and the environment and will recommend practices for leachate control, gas migration control and groundwater monitoring. A working draft of the Landfill Guideline was circulated last uear and a proposed version should be published in the Federal Register for public comment by March of 1979.

Other guidelines to be developed in the future will cover landfarming of solid waste and surface impoundment disposal. In addition, preparatory work is underway to develop guidelines on the management of two special waste categories: coal-fired electric utility wastes and mining wastes. In cooperation with the Office of Research and Development programs are being initiated to evaluate facilities that dispose of fly ash, bottom ash, and scrubber sludge from coal-fired utilities and wastes from metals and phosphate mining and beneficiation processes and uranium mining. Thirty to forty facilities will be evaluated over a period of two years in order to assess practices for managing such wastes.

Finally a guideline is being developed for the disposal and utilization of wastewater treatment plant sludge under the combined authorities of RCRA and Section 405 of the Clean Water Act. This guideline will discuss practices for landfilling sewage sludge, use of sludge as a soil conditioner on agricultural lands, thermal processing of sludge for energy recovery, and sludge composting or heat drying to produce a bulk or bagged product. These guidelines will be proposed in mid-1979 with final promulgation expected in 1980.

Section 405 of the Clean Water Act requires compliance with such guidelines by operators of publicly owned wastewater treatment works and it is expected that these guidelines will be administered through the National Pollution Discharge Elimination System permit process.

Technology Demonstrations and Technical Information

The Office of Solid Waste has several projects underway to demonstrate and evaluate improved techniques for disposing of solid waste on land.

In Tullytown, Pennsylvania, leachate from an asphalt-lined landfill is collected and treated by a number of physical and biological methods. The leachate treatment plant has been operating for several years and a number of EPA reports have described its operation. The final project report was received in early 1979 and should be publicly available shortly. The treated leachate is discharged to a nearby river in conformance with standards established by the State.

In 1979, full-scale operation of another leachate treatment facility in Enfield, Connecticut is expected to begin. This facility, based upon research conducted by the EPA, Office of Research and Development and the University of Illinois, uses an anaerobic filter to treat leachate. One of the features of this system is the low volume of sludge produced. The final report on this project is expected in mid-1980.

A full-scale lined landfill demonstration is underway in Lycoming County, Pennsylvania. After several years in development, a landfill employing a PVC liner to collect leachate began to receive wastes in early 1978. A report will be available in 1979 covering among other things, procedures for installing a liner sheet covering a large area. Two other lined landfill demonstrations in Northern Tier, Pennsylvania are expected to start in 1979.

In Bangor, Maine the Office of Solid Waste is participating with the City in demonstrating a process for composting sewage sludge. This project is based upon the aerated-pile process for composting sludge developed by the U.S. Department of Agriculture in Beltsville, Maryland. This demonstration represents the first on-line application of this process in a small community. It has proven very successful and composted sewage sludge has been sold and used as a soil conditioner for over a year. An interim report was published in 1977 and a final report is due in 1979.

In Mountain View, California a very innovative project involving the recovery of methane from a landfill is underway. In a joint effort involving the City, the Pacific Gas and Electric Company and EPA, methane gas is pumped from a landfill, cleaned up, and injected into a nearby pipeline supplying gas to residential users. This project not only prevents the safety problems that could result from the migration of gas from the landfill, but also recovers and utilizes a valuable resource. The facility has been operational for nearly a year, interim reports are available, and a final report is expected in mid-1979.

The Office of Solid Waste also prepares a number of technical reports on various subjects pertaining to land disposal. One such report that was very well received was a procedures manual for monitoring leachate and groundwater around disposal facilities. We also have an ongoing effort to monitor groundwater at a number of disposal sites both to improve monitoring techniques and gain a better understanding of leachate and groundwater interaction. Other technical reports under development include an assessment of methods to prevent and control migration of toxic or explosive gases at disposal sites and an evaluation of procedures to prevent hazards to aircraft from birds atrracted to disposal facilities.

The Office of Solid Waste also participates in the review and evaluation of the wide range of research and development projects in the land disposal area conducted by the Office of Research and Development and described in other papers at this Symposium.

RESOURCE RECOVERY AND CONSERVATION

Resource recovery and conservation activities will be grouped into three categories for discussion:

1. activities of the Resource Conservation Committee
2. guidelines for Federal agencies, and
3. demonstrations, evaluations and studies.

Resource Conservation Committee

The Resource Conservation Committee was established by Section 8002(j) of the Act. It is a Cabinet-level committee chaired by the Deputy Administrator of EPA and supported by OSW staff. The Committee is required to conduct "a full and complete investigation and study of all aspects of the economic, social, and environmental consequences of resource conservation." To obtain public input for these studies, the Committee held several hearings on beverage container deposits, solid waste disposal charges, the effect of existing Federal tax and transportation policies on the use of virgin and secondary materials, recycling and resource recovery sibsidies, deposits or bounties on durable goods, local user fees, litter taxes, severance taxes, and product regulation.

The first resource conservation issue taken up bu the Committee was beverage container deposits. In its January 1978 report to the President and Congress, the Committee presented a recommended design for beverage container deposit legislation. The Committee did not recommend that such legislation be passed, however; a decision on this issue was postponed until further analyses were completed.

In its July 1978 report to the President and Congress, the Committee submitted preliminary analyses of solid waste disposal charges. Work is continuing on beverage container deposits and solid waste disposal charges and the results of these and other analyses will be presented in the Committee's final report along with recommendations. This report is scheduled for completion in March 1979.

Guidelines for Federal Agencies

On April 23, 1976, EPA issued Guidelines for Source Separation for Materials Recovery. These guidelines require the recovery of highgrade paper, newsprint, and corrugated boxes from Federal facilities. As a result, 175,000 Federal employees in 135 Federal facilities are participating in the paper recycling programs. It is expected that another 100,000 employees will be in the program by October 1979. OSW has worked with the General Services Administration in establishing contract procedures for the sale of the paper and in developing an educational program for training Federal employees in procedures for recycling office paper. To date, over 2,000 tons of paper have been recycled under the guidelines with a return to the Federal Treasury of over $125,000. In addition, at least 15 states and hundreds of local governments have adopted the guidelines.

On September 21, 1976, EPA issued Guidelines for Beverage Containers. These guidelines require that a refundable 5-cent deposit be placed on all containers for beer and soft drinks sold at Federal facilities. The deposit is intended to encourage the return of containers for either refilling or recycling. The Department of Defense concluded a test of the guidelines at 10 military bases in June 1978 and will submit its plans based on this test in early 1979. The General Services Administration also conducted a test of the guidelines in 8 of its 10 regions. To date, 13 Federal agencies are implementing the guidelines. The OSW monitors agency compliance with the guidelines and provides assistance upon request.

On September 21, 1978, EPA issued Resource Recovery Facilities Guidelines. These guidelines contain requirements and recommended procedures for Federal agencies regarding establishment and use of resource recovery facilities. To date, some degree of implementation has been reported by Federal agencies in nine metropolitan areas.

Procurement Guidelines are currently being developed under Section 6002 of RCRA. Al agencies procuring with Federal funds (including State and local governments, grantees, and contractors as well as Federal agencies) must "procure items composed of the highest percentage of recovered materials practicable." The guidelines for recommended procurement practices will contain information regarding suppliers, demand, price, delivery time, performance, and certification techniques.

OSW is now gathering data on products purchased by the government that may have high potential in the use of waste materials. Studies include:

1) The use of fly ash and blast furnace slag in cement and concrete. 2) The use of wastepaper in insulation and board; waste rubber in asphalt pavements; and concrete. 3) The use of wastepaper and other secondary fibrous materials in paper products and 4) The use of composted sewage sludge used as a soil conditioner and low-grade fertilizer.

The first guideline, scheduled to be proposed in April 1979, will be on the use of fly ash and blast furnace slag in cement and concrete.

Demonstrations, Evaluations and Studies

The OSW is involved in the demonstration and evaluation of the technical, economic and environmental performance of a number of resource recovery systems.

Two of the early demonstration projects developed technologies that are being replicated in a number of communities. The first, in Franklin, Ohio, determined the feasibility of using the wet-pulping method of separating mixed municipal solid waste into organic and inorganic fractions. Follow-on applications of this technology will use the organic fraction of the solid waste as a fuel.

The second demonstration, in St. Louis, Missouri, developed the technology of recovering a portion of the organic fraction of the mixed municipal waste stream for use as a supplement to coal in large boilers. This technology is being replicated in 10 locations. An extension of this concept that includes utilization of sewage sludge is being demonstrated under a grant to the State of Delaware.

Two systems for recovering energy from mixed municipal solid waste through pyrolysis were demonstrated in Baltimore, Maryland, and San Diego County, California. The Baltimore plant, which produces steam by combusting the pyrolysis gases, has had numerous mechanical and air pollution problems and is presently undergoing an extensive modification program. After the modifications are completed, it is anticipated that the process will run in an economically and environmentally sound manner. The San Diego project also experienced difficulties and is currently not in operation. Although it is doubtful that either of these systems will be replicated in toto, much was learned concerning the pyrolysis of solid waste, and this information should prove useful to others considering this process.

Six projects to develop source separation systems are now nearing completion. Projects in Marblehead and Somerville, Massachusetts, were started three years ago to determine the feasibility of separate collection techniques to recover several materials from municipal waste streams. These two programs have shown that it is possible to recover between 25 and 30 percent of the residential waste stream in suburban communities. Approximately 15 to 20 other multimaterial collection programs have begun in the New England area as a result of the increased municipal and industru interest created by the Marblehead/Somerville projects. A final report presenting the results of this project will be issued in 1979.

Four projects were started two uears ago on: multimaterial collection through private contract; multimaterial collection from apartment buildings; source separation and materials marketing for low-density rural areas; and the use of handicapped laborers for processing materials. Final reports will be issued in 1979.

In addition to EPA-supported demonstrations of resource recovery systems, OSW is also conducting evaluations of other commercial-scale resource recovery facilities: refuse-derived fuel plants in Lane County, Oregon, and Chicago, Illinois; small modular incinerators with heat recovery; waterwall combustion units in Europe; a plant for codisposal of sewage sludge and municipal solid waste in Duluth; and a pyrolysis system in Frankfort, Germany. Evaluations of system components such as air classifiers and shredders are also underway.

In cooperation with the Office of Research and Development, OSW is conducting studies on resource recovery as required by section 8002 of the Act on the subjects of: 1) compatibility of source separation and mixed waste recovery, 2) small-scale technology, 3) research priorities for resource recovery and 4) tire, glass and plastics recovery.

FINANCIAL AND TECHNICAL ASSISTANCE TO STATE AND LOCAL GOVERNMENTS

The Resource Conservation and Recovery Act places the primary responsibility of improving solid waste management on State and local governments. The Act provides for a number of financial and technical assistance programs for assisting in that effort.

Financial assistance is available to develop and implement comprehensive State solid waste management plans under Subtitle D of the Act. Guidelines to assist in the development and implementation of State solid waste management plans were published in proposed form in August 1978 and will be finalized in June 1979. These plans should provide for (1) regulatory programs for environmentally sound disposal of all other solid wastes, (2) State programs to encourage resource recovery and conservation, and

(3) planning for necessary disposal and recovery facilities. In fiscal year 1979, $11.2 million was available for these purposes.

A new financial assistance program resulting from the President's Urban Policy Message will help communities to adequately assess the feasibility of resource recovery projects and obtain sufficient consultation and staff for the preparatory steps in implementation. This program is scheduled to begin in fiscal uear 1979 and $15 million has been appropriated for the first year. Urban areas will be eligible for assistance for "front-end" steps preceding actual design and construction of resource recovery projects. This includes not only mixed waste resource recovery processing plants but also projects involving source separation (i.e., separation at the place of generation) of waste materials for recycling. Eligibility for funding is not limited to large cities, but a major portion of the funds will probably go to jurisdictions of at least 50,000 population. The aid will go primarily to agencies with clear responsibility for implementation as designated in the State planning process udner Subtitle D. The first set of applications were received in December 1978 and awards are expected to be made in March or April 1979.

The Act also provides for technical assistance through the Technical Assistance Panels Program. Each EPA regional office has available a panel of expert consultants capable of assisting in all areas of solid waste management. Grants have been provided to a number of public interest groups to make State and local government officials available to provide assistance as well. These panels are available to provide technical assistance free of charge to State and local governments and Federal agencies upon request. Twenty percent of the funds appropriated under the general authorization of the Act are used for this purpose.

The OSW has developed a seminar series directed mainly at municipal officials. A first set of seminars presented alternatives and major issues in the implementation of resource recovery. In 1978 the seminar was conducted in six cities; approximately 1,000 people attended. The seminar program will continue into 1979 and will be expanded to cover other solid waste management issues as well.

The Resource Conservation and Recovery Act provides an opportunity for significant advancements in solid waste management nationwide. The regulations and guidelines provide momentum and impetus for improved practices. Technology demonstrations, evaluations and studies will help provide necessary technical, economic and environmental performance information so that better decisions can be made. Financial and technical assistance programs will provide additional resources to State and local governments responsible for implementation. The Office of Solid Waste programs in these three areas are an attempt to provide a balanced approach to this nationwide effort.

USEPA REGION 4 SOLID WASTE MANAGEMENT ACTIVITIES

Elmer G. Cleveland
U.S. Environmental Protection Agency
345 Courtland Street
Atlanta, Georgia 30308

In the beginning -- in this instance the late 1960s -- solid waste management in Region 4 was at best completely inadequate even by standards prevailing at that time. Before getting into an update on regional solid waste management activities we must look at our beginning.

Prior to the passage of the Solid Waste Disposal Act of 1965, there did not exist an identifiable state solid waste program in the region. A survey of land disposal sites in the late 1960s indicated over 2500 dumps and fewer than 30 sanitary landfills which could meet the very loose requirements that prevailed at that time. By 1971, total state solid waste program positions were 42.

State solid waste laws were enacted, viable programs established, regulations promulgated, and state plans developed. Inspection and technical assistance programs were put into action.

By 1977, over 1000 land disposals met or exceeded the minimum requirements to be termed a sanitary landfill and permitted or approved by the state programs. State program personnel now exceeds 225 with increases scheduled to take on the additional duties associated with hazardous waste and resource recovery.

While maintaining the successful level of solid waste management attained, a combined federal, state and local governmental effort is underway to correct and eliminate existing and potential environmental hazards from old disposal practices. New and environmentally sound hazardous waste processing and disposal facilities are being designed and constructed. Some are now in operation.

Resource recovery facilities are in operation, under construction, and being planned. Under the President's Urban Policy, which provides financial assistance for Resource Recovery Project Development, more than thirty applications requesting over $3.5 million in Federal assistance were received from this region. The Department of Energy has solid waste demonstration projects in Alabama, Florida and Georgia.

EPA funding of state solid waste programs in Fiscal Year 1979 will exceed four million dollars. Technical assistance through Section 2003 of the Resource Conservation and Recovery Act has been delivered to more than 30 local governments at an approximate cost of $200,000. This was provided at no cost to the clients, i.e. local governments.

In the 1980s, we expect to achieve a level of solid waste management, hazardous waste control and resource recovery that should meet our immediate needs and set examples for the rest of the Country.

CURRENT RESEARCH ON RESOURCE RECOVERY

Albert J. Klee, Ph.D.
Steven C. Lees
U.S. Environmental Protection Agency
Cincinnati, Ohio 45268

ABSTRACT

The Resource Conservation and Recovery Act of 1976 (RCRA) charges the U.S. Environmental Protection Agency with the responsibility of providing "technical and financial assistance for the development of management plans and facilities for the recovery of energy and other resources from discarded materials and for the safe disposal of discarded materials, and to regulate the management of hazardous waste." The Solid and Hazardous Waste Research Division (SHWRD), Municipal Environmental Research Laboratory (MERL), Cincinnati, Ohio, has many technical responsibilities required for fulfillment of this Act. Research is performed in a variety of technical, economic, and institutional areas, reflecting the broad opportunities and requirements in the recovery of resources from wastes.

Although the SHWRD, Processing Branch, has research projects dealing with hazardous waste management and control technologies, this paper examines, in an overview fashion, the current research efforts relating to resource recovery and the improved management of municipal solid waste (MSW). This research ranges in scope and complexity from short-term institutional systems analyses to full-scale, long-term demonstrations of developed Resource Recovery Technologies. To address adequately the many facets of resource recovery, research has necessarily been diverse; however, all efforts lead to the goal of full utilization of the resources available in our refuse. Accordingly, this paper is presented to bring together the many individual projects into a unified, comprehensive strategy available for management of these wastes.

The format of this presentation follows the general strategy used to conceptualize, plan, design, construct, and operate a resource recovery system. Specifically, the following general areas are discussed: (1) Waste Forecasting, (2) Systems Analyses, (3) Processing, (4) Materials Recovery and Reuse, (5) Refuse Derived Fuels, (6) Alternative Resource Recovery Options, and (7) Pollution Control.

INTRODUCTION

In 1976, annual municipal solid waste generation was estimated to be approximately 130 million metric tons. Every individual in the United States contributes roughly 1,300 pounds to this figure. By 1985, the yearly total is projected to increase to 180 million metric tons. What happens to this waste? By and large the majority is destined for land disposal, with no recovery of resources or available energy and with its inherent problems of leachate and gas control to avoid water, air, and crop pollution. As of 1977, only 7 percent of the waste stream was recovered. Of this, 90 percent was source-separated paper. In fact, the business of commercial resource recovery has accounted for less than 1 percent of the total wastes generated. Many resource recovery facilities have not achieved success due to economic, technical, and institutional constraints. Poor planning, retrofitted equipment, over-rated waste flows, and institutional and market problems have all been blamed, with some degree pf validity. The long range solution to this problem is proper planning, selection of equipment specifically designed for refuse and implemented in the optimal process scheme, development of markets for recovered commodities, and overcoming of minimizing any institutional or social uncertainties. Simply stated, resource recovery is much more complex than originally anticipated, and more research and development is required.

The research performedby the SHWRD is designed to aid in this long range solution. The format adopted for this paper attempts to class the research activities into categorical areas applicable to amny resource recovery options. Some research activities are singular and defy classification, and the same holds true for some resource recovery activities. By the identification of similarities in processes, the problems encountered, their causes and fixes, and the research requirements, a qualified decision can be made as to the viability of a total resource recovery system. It is the purpose of the SHWRD research program to help in making these decisions.

WASTE FORECASTING

Many resource recovery facilities have not had the benefit of actual area waste surveys prior to design and construction of the plant. Examples include Ames, Baltimore County, and the El Cahon facility. Many other facilities simply relied on "National" figures as gross estimates of quantity and composition, as was the case at Franklin's wet processing plant. The lack of reliable data on quantity and composition has manifested itself in many negative ways, including inadequate total waste flow to fully utilize the equipment installed. Other examples include low aluminum loading, unusually high moisture and ash contents, or extreme seasonal fluctuations.

The necessity for accurate quantity/composition data prior to design has generally been established. However, numerous methodologies have been employed to gather this information, with varied degrees of accuracy. The initial effort in waste forecasting by SHWRD (1) is identifying, developing, and comparatively evaluating several methodologies for accuracy in estimating total quantity and waste composition. Concurrently, the project is determining to what degree of accuracy these variables must be estimated to insure proper design of the facility. Many communities, private organizations, and institutions have been surveyed to determine the methodologies used, their success in predicting actual quantity and composition, and the identified shortcomings. The output of this research will be a developed protocol for conducting a composition and quantity study, including appropriate "cross-checks" to insure accuracy. This developed protocol will then be implemented in the context of a field test.

Whereas the above study will provide a protocol for determining a municipality's "immediate" waste scenario for establishing a resource recovery system, the second effort (2) in this area is to establish solid waste quantity and composition trends on a national level. Such factors as increased use of packaging materials, substitution of plastic for steel in certain applications, and beverage container deposits, will be evaluated and their effects projected on a national level to the year 1990. The information obtained will be used in determining national waste trends and the implications for collection, disposal, and resource recovery.

To provide users with the data obtained in these two projects, along with data on collection and disposal costs, a solid waste data base is being developed (3). This project will incorporate the methodologies developed above, solicit additional data needs, and provide for a mechanism of continual updating. A questionaire format will be developed to assist in this update as well as to track the success or failure of the forecasting methodologies as implemented. Ultimately, this solid waste data system will provide information on many municipalities' "immediate" waste scenarios as well as tracking national solid waste quantity, composition, and collection/disposal costs. A training program for data gatherers will ensure accurate responses to the questionaire. As State Solid Waste management programs are implemented, this system should provide the information to perform comparative analyses.

SYSTEMS ANALYSES

Social, economic, and istitutional factors affecting the implementation of resource recovery facilities or improved waste management techniques are addressed under Systems Analyses. Perhaps the most comprehensive effort in this area is the one initiated in response to RCRA, Section 8002 (4). Designed to identify the impediments to economical operation of resource recovery facilities, this effort should identify the inhibiting factors that have plagued most operating facilities. These factors will be quantified, related to research needs, and ranked to signify which, when removed, will contribute most to the successful operation of resource recovery facilities. Based on these results submitted to the EPA Administrator, a plan for research, development, and demonstration will be submitted to the appropriate committees of Congress.

Several other mechanisms for improved waste management and waste reduction are also being explored. Based on the limited success of the source separation programs prevalent in the Northeast, research is underway to identify the socio-economic classes of society most likely, and least likely, to participate in such programs (5). This research involves analyzing results from several types of media campaigns and public information systems to determine the most effective mechanism for stirring increased participation.

User charges for collection and disposal have been adopted by several cities in the United States as a mechanism for improved waste management. The first project dealing with user charges (6) developed a descriptive list of the communities using user charges and categorizing them into five general catagories. Case studies are being performed in selected communities representing each general catagory. To the extent that data are available, the effects of user charges on per capita generation rates, composition of refuse, household preferences for optional levels of service, and alternative disposal modes (including resource recovery) will be measured.

Concurrently, the SHWRD is monitoring and assisting the City of Seattle's variable user charge experiment (7). Along with providing assistance in experimental design, development, and implementation of evaluative methodologies, EPA is also assisting with data gathering and techniques for cost analysis, data gathering and techniques for demand and benefit analysis, including the relevant elasticities of demand, and implementation of the rate structure. Results will be evaluated for implications to solid waste collection, disposal, and source separation.

Institutional systems designed to favor the use of virgin materials have been cited as one major reason operating resource recovery facilities have suffered economically and, on a larger scale, why capital investments in such systems have been avoided. The problem appears to include three major areas: Freight rates for secondary materials, the availability of markets for the recovered commodities, and the establishment of standard specification and analysis procedures for MSW and MSW-derived products. To quantify the effects of the secondary material freight rate structure, a theoretical demand model incorporating transportation costs as a factor in the demand for investment is being developed (8). This model will be adapted to investment decisions by the raw steel-making and ferrous foundry industries, and will be specified to permit emperical testing at a future date.

An economic analysis of scrap futures markets is underway to determine whether scrap materials are amenable to futures trading, shether futures markets would encourage capital inflow to the scrap industry, and what the benefits and costs would be to market participation and to society (9).

In cooperation with the ASTM E-38 Commitee on Resource Recovery, standard procedures for sampling and analysis of MSW (especially RDF and other recovered materials) are being developed (10). Several candidate procedures and methodologies have been compiled, reviewed, and consolidated into an Interim Standard Procedure. Round-Robin testing techniques are being employed to test the validity of the procedures.

PROCESSING

Operations on refuse prior to the recovery of the energy value of the light fraction or disposal by landfilling has been termed "processing." These processing operations usually involve some form of communition, separation or classification of the various components, and preparation of the combustible fraction for ultimate end-use. The equipment or unit operations used in these processing activities are numerous and not fully understood, especially in relation to one other when designing a total process scheme.

The SHWRD has ongoing research to define the design and operational parameters needed for evaluation and selection of these equipment items.

The first effort in processing research (11) is being performed at the National Center for Resource Recovery, Equipment Test and Evaluation Facility (ETEF). Various unit processing hardware, including shredders, air classifiers, screens, conveyors, and gerrous and non-ferrous separators, are being evaluated and developed. Numerous performance characteristics, curves of effectiveness, and comparative advantages and disadvantages have been established. Economic aspects are also being addressed relative to operating and maintenance costs.

Whereas the previous research has been performed at pilot scale, several projects are evaluating and optimizing full-scale operational systems. The Recovery I facility in New Orleans is undergoing a series of test evaluations to establish performance, maintenance requirements, economics, and optimal sequencing of the various mechanical processing equipment (12).

Specific equipment items to be evaluated include the trommel, air classifier, ferrous recovery system, aluminum recovery system, glass recovery system (jigging and crushing), glass cleanup system (flotation), glass drying system, and the nonferrous recovery system.

To supplement the research results obtained at Recovery I, several other facilities and selected equipment items are being evaluated (13). This effort deals primarily with processes and/or equipment designed and operated for production of a fuel or a fuel feedstock. First efforts have identified the state-of -the-art of processing equipment and the research requirements. Test plans were then formulated and field tests conducted to meet some of these research needs.

Several equipment items have been identified as almost universal components of resource recovery facilities. Of these, the shredder and air classifier are of the most interest, since the shredder consumes the most energy of any piece of processing hardware and the air classifier directly controls the quantity and quality of the recovered combustible fraction. To evaluate different shredder designs comparatively, research is being performed at several operational facilities with different shredder designs (14). Several horizontal shaft hammermills are being evaluated, as well as some newer designs, including a vertical shaft ring gear grinder, a reversible rotation horizontal shaft hammermill, and a vertical shaft hammermill. Performance and operating data will be obtained as well as analyses of the MSW processed by the shredders.

To more fully understand teh effectiveness of the operation of various air classifier designs, a study has been initiated to document several performance characteristics of all the designs tested (15). This effort should also produce a standard protocol and testing procedures for use in other air classifier evaluations.

MATERIALS RECOVERY AND REUSE

SHWRD is conducting three studies in this area in response to RCRA, Section 8002. The first effort deals with identifying and prioritizing research needs for energy and materials recovery (16). This prioritization will then be evaluated as to the type and extent of Federal assistance required to satisfy the identified research needs.

Secondly, a survey of the state-of-the-art of glass and plastic recovery will identify and assess the potential problems and solutions associated with increased recovery of these commodities (17). The quantity of waste generated, recovery methods and technical feasibility, economics, environmental impacts, markets, and industry-required specifications are just some of the factors to be weighed in this study.

The problems and potential of improved waste automobile tire management will be addressed in the third RCRA special study (18). The current state of recovery and reuse will be identified, as well as the prevailing trends directed by technical and economic factors.

The SHWRD has sponsored research for several years on the use of waste glass in structural clay brick manufacture (19). The composition of the waste glass recovered, typically containing 10-30 percent organics, has been evaluated both technically and economically relative to effects in the manufacture and furnace curing of the bricks. The use of these "waste glass slimes" now appears technically feasible, and the energy requirements in the brick curing stage have also been reduced.

REFUSE DERIVED FUELS

One of the most promising energy recovery technologies available is the use of densified refuse derived fuels (d-RDF) for combustion with coal in existing utility, institutional, and industrial stoker boilers. extensive research is being performed on d-RDF production, including identifying the optimal processing scheme and quantifying the effects of combustion.

The first efforts in d-RDF production were to investigate the technical and economic aspects of preparation and use (20). Important characteristics required for a specification d-RDF were identified and measured. The first 300 tons produced were co-fired with coal at the Maryland Correctional Institute, Hagerstown, Maryland. Based on the results of this test burn, which produced minimal handling and feeding problems as well as acceptable emissions, d-RDF production was continued at the National Center for Resource Recovery (ETEF) to allow for a second, more comprehensive test burn. Along with the 900-1200 tons being produced by NCRR, an additional 2000 tons of d-RDF have been purchased. This second test burn is scheduled to be at the General Electric Plant, Erie, Pennsylvania (21). The data gathered during this burn should provide industry and utilities with sufficient information to decide as to the viability of this energy recovery option in their particular situation.

During the initial phases of production at NCRR, it became evident that certain fundamental considerations in d-RDF production were lacking. A study was initiated to address these basic theoretical considerations, and to relate these concepts to large scale production (22).

Besides co-firing d-RDF in stoker boilers, research is being performed to determine the requirements for a refuse derived fuel for use in cement kilns (23). Fuels used in cement kilns are typically finely shredded or pulverized coal, so process modifications in RDF production will be required. These processing and preparation requirements will be addressed in anticipation of actual field testing.

ALTERNATE RESOURCE RECOVERY OPTIONS

Although the use of densified RDF has received the most widespread attention as an energy recovery technology, it is but one of many alternatives being explored by the SHWRD.

Exploratory research is being performed to identify and develop chemical and thermal processes for improving the fuel quality of the air-classified combustible fraction (24). This work has centered on cellulose embrittlement techniques, although other processes have been evaluated, such as carbonization.

Two RCRA special studies are also being conducted in this category. The first effort is reviewing and analyzing systems of small-scale and low technology solid waste management, including resource recovery and resource recovery systems which have special application to multiple dwelling units and high density housing and office complexes (25). The degree of contribution of these systems to energy recovery and consercation is also being evaluated.

The second study in response to RCRA is investigating and defining the compatibility of a source separation program with a high technology resource recovery system (26). Various levels of source separation and the related effects are being investigated, with an economic determination of the optimal combination of the two approaches.

Getting away from what may be considered "conventionsl" resource recovery as discussed earlier, several research efforts are exploring the potential for energy recovery from MSW through other means.

The feasibility of constructing and operating landfills to optimize the production and recovery of methane gas is under investigation (27). Various factors are being defined, such as recovered methane quality, landfill chemistry as related to increased biodegration, and waste quantity and composition effects.

Mehthane production from anaerobic digestion of a mixture of sewage sludge and MSW is also being explored (28). Gas and mechanical mixing mechanisms are being evaluated for effects in the pilot-scale operation. Several factors, such as retention time, MSW/sewage sludge mixing ratio, and loading rate are being studied.

Chemical treatment of various urban and agricultural wastes is being performed for the determination of the efficacy of the process in producing methane and organic acids (29). This research effort involves conversion of the cellulosic materials into a fermentable substrate by alkali pretreatment, anaerobic fermentation with selected acid generation bacteria, and carboxlic acid recovery by dialysis, coupled with soluable ion exchange polymers.

The SHWRD's largest effort in alternative resource recovery options is the acid hydrolysis system, now at the one ton per day pilot plant level (30). After two years of study with a 1 liter and 5 liter reactor, it was determined that cellulosics pretreated with 1% sulfuric acid at temperatures around 450 °F, resulted in up to 50% conversion to glucose in reaction times as short as 10-20 seconds. In addition, the surgars produced appear to be convertible to ethyl alcohol and single cell proteins.

In light of the problems experienced with the storage of the pyrolytic oils produced at El Cajon and elsewhere, our research in utilization and stabilization of pyrolytic oils has gained in importance. Ongoing for several years, early research efforts focused on physical processing of the oil and characterization of the products and fractions obtained (31). Subsequent efforts dealt with chemical processing of these fractions to obtain commercially useable products. Research efforts in a concurrent program have attempted to elucidate the mechanism involved in the change in viscosity of the pyrolytic oils (32). A combined gas chromatographic-mass spectrometric (GC-MS) and liquid chromatographic (LC) analysis acheme is being developed to identify the many components of the oil, and the chemical changes occuring that produce the increased viscosity. At this time it appears that recovery of phenols, and hence production of phenol-formaldehyde resins, is feasible.

POLLUTION CONTROL

To insure that the energy or material recovery techniques being developed are environmentally acceptable and produce a net positive gain to society and the environment, research is being performed to determine the areas of importance in pollution control. The SHWRD currently is involved in several research projects in this area.

The most comprehensive effort, performed in coordination with the Industrial Environmental Research Laboratory (IERL), Cincinnati, involves development of air pollution control technology for wastes as fuels processes (33). Primary efforts have been in testing and development of improved fabric filters for a variety of systems, such as RDF and mass burning. Preliminary investigations are also being conducted on design of an improved wet scrubber system.

The potential environmental benefits and effects of increased resource recovery are being quantified in another research project (34). Primary emphasis is placed on the effects on landfilling and incineration, and the subsequent reductions in leachate production and air pollution.

Research is also being conducted on the emissions from processing and bioconversion systems (35). Preliminary assessment criteria and pollutant measurement techniques have been defined, and the pollutants have been characterized from a processing and a bioconversion system. Based on these results, an analysis of applicable control techniques will be perfromed.

During the operation of the St. Louis RDF project, cursory sampling at selected locations revealed higher-than-background levels of bacteria, causing concern over the potential health implications. A study was subsequently performed to gather additional data at and around the processing facility (36). Results indicated that there were increased levels of bacteria present. However, data does not exist to identify or quantify absolutely the health effects.

Lead and other trace metal emissions from facilities burning RDF have recently received attention due to the sampling and analyses work performed at Ames, along with the promulgated $1.5\ ug/m^3$ ambient air standard. A research contract, therefore, was awarded to identify the sources of lead in RDF and the chemical composition of these lead contributing products (37). These sources will be traced through the processing stages, and any phenomenon of transformation in combustion will be identified and related to emissions. The infromation developed will aid in determining the seriousness of this problem, and the applicable control techniques.

CONCLUSION

Realizing that the many specific research areas discussed in this overview will be covered in greater detail later in this symposium, some discussions were necessarily brief. Interested parties are urged to attend the individual presentations, and for more detail or reports, contact the EPA project officers referenced and listed at the end of this paper.

REFERENCES

1. Municipal Solid Waste Protocol, SCS Engineers, Project Officer, Albert J. Klee

2. Forecasting The Quantity and Composition Of Solid Waste, International Research and Technology, Project Officer, Oscar W. Albrecht

3. Development of A Solid Waste Questionnaire And Data Base, Project Officer, Oscar W. Albrecht

4. Evaluation Of Impediments To Economical Resource Recovery, Mathtech, Project Officer, Oscar W. Albrecht

5. Source Reduction of Product Packaging from Households: An Evaluation of Public Information Systems, Univ. of Arizona, Project Officer, Haynes Goddard

6. User Charges For Managing Household Wastes, Mathtech, Project Officer, Oscar W. Albrecht

7. Evaluation Of The Seattle Variable User Charge Experiment, University of Washington, Project Officer, Haynes C. Goddard

8. Research Design For Freight Rate Study, Dr. William Whitmore, Project Officer, Oscar W. Albrecht

9. Economic Analysis Of Scrap Futures Markets for Stimulation OF Resource Recovery, Environmental Law Institute, Project Officer, Oscar W. Albrecht

10. Compilation, Development, And Testing Of Interim Standard MSW Procedures, ASTM, Project Officer, Carlton C. Wiles

11. Materials Recovery And Side By Side Evaluation Of Selected MSW Preprocessing Equipment, National Center for Resource Recovery, Project Officer, Donald A. Oberacker

12. Resource Recovery Unit Process Test And Evaluation At Recovery I, National Center for Resource Recovery, Project Officer, Donald A. Oberacker

13. Preprocessing Equipment For Resource Recovery, Midwest Research Institute, Project Officer, Donald A. Oberacker

14. Field Test Evaluation Of Selected Shredder Designs, Midwest Research Institute, Project Officer, Donald A. Oberacker

15. Comparative Study of Full Scale Air Classifiers, Midwest Research Institute, Project Officer, Stephen C. James

16. Priorities Assessment Of Material nad Energy Recovery Needs, National Academy of Science, Project Officer, Oscar W. Albrecht

17. Resource Recovery Of Glass and Plastic Wastes, Pacific Environmental Services, Project Officer, Stephen C. James

18. Status, Trends, and Impediments To Discarded Tire Collection And Resource Recovery, Urban Systems, Project Officer, Haynes C. Goddard

19. Technical Evaluation And Market Study On The Use Of Waste Glass Mixtures In Structural Clay Brick Manufacture, Occidental Research Corporation, Project Officer, Donald A. Oberacker

20. Preparation Of Refuse Derived Fuels, National Center for Resource Recovery, Project Officer, Carlton C. Wiles

21. Effects Of Burning Densified RDF In Stoker Boilers, Systech, Inc., Project Officer, Carlton C. Wiles

22. Fundamantal Considerations In The Production Of d-RDF, University of California, Carlton C. Wiles

23. Processing And Preparation Of RDF For

Cement Kiln Firing, Maryland Environmental Services, Project Officer, Donald A. Oberacker

24. Concepts For Improving The Fuel Quality Of RDF, University of Dayton Research Institute, Project Officer, Albert J. Klee

25. Small-Scale, Low Technology Study, SCS Engineers, Project Officer, Donald A. Oberacker

26. Source Separation/Resource Recovery Compatibility, Gilbert Associates, Project Officer, Stephen C. James

27. Methane Recovery From Landfills, Lockman & Associates, Project Officer, Stephen C. James

28. Gas And Mechanical Mixing Of Sewage Sludge/MSW Mixture, Systech Inc., Project Officer, Stephen C. James

29. Methane And Volatile Fatty Acids From Chemical Treatment Of Agricultural Residues, Louisiana State University, Project Officer, Charles J. Rogers

30. Acid Hydrolysis Of Cellulose, New York University, Project Officer, Charles J. Rogers

31. Upgrading And Mehtods Of Stabilization Of Pyrolytic Oils, Georgia Tech Research Institute, Project Officer, Charles J. Rogers

32. Development Of Methods For Stabilization Of Pyrolytic Oils, Atlanta University, Project Officer, Charles J. Rogers

33. Air Pollution Control Technology For Wastes As Fuels Processes, Pedco Environmental, Project Officer, Donald A. Oberacker

34. Assessment Of The Impact Of Resource Recovery On The Environment, Mitre, Project Officer, Albert J. Klee

35. Environmental Assessment Of Wastes As Fuels Processes, Midwest Research Institute, Project Officer, Carlton C. Wiles

36. St. Louis Bacteria/ Virus Testing, Midwest Research Institute, Project Officer, Carlton C. Wiles

37. Lead And Other Trace Metals In MSW, York Research Corporation, Project Officer, Donald A. Oberacker

AN OVERVIEW OF THE DEPARTMENT OF ENERGY'S RESEARCH, DEVELOPMENT AND DEMONSTRATION PROGRAM FOR THE RECOVERY OF ENERGY AND MATERIALS FROM URBAN WASTE

Alan S. Cohen
Energy and Environmental Systems Division
Argonne National Laboratory
Argonne, Illinois 60439

ABSTRACT

The Urban Waste Technology Branch of the Department of Energy is conducting a comprehensive and diversified research, development, and demonstration program to foster the widespread use of urban waste as a source of energy and materials. This program is directed at improving and developing technologies that reprocess waste into fuels, metals, glass, paper, ammonia, glucose, fertilizers and other energy intensive products. Nontechnical issues relating to institutional, socioeconomic, and legal constraints to resource recovery are also being investigated.

This paper briefly describes the technological options available in the field of resource recovery. Some of the approximately 80 projects comprising the Urban Waste Technology Branch's research, development, and demonstration program are discussed and related to the overall objectives of the branch. To facilitate this presentation, projects are grouped as being primarily related to mechanical, thermal or biological processes.

To date the majority of research and development funding has been devoted to biological processes including anaerobic and enzymatic digestion, energy production and conservation in water and wastewater treatment, and energy generation and recovery in sanitary landfills. However, demonstration activities, representing slightly less than half the program effort, are focused on the thermal/mechanical systems.

DOE activities are coordinated with the EPA and other federal, state and local efforts in resource recovery to ensure the development of an efficient and comprehensive national resource recovery program. If successful, approximately 3% of the nation's energy needs could be supplied by reprocessing wastes.

INTRODUCTION

The Urban Waste Technology (UWT) Branch of the Department of Energy (DOE) has as its primary objective the widespread use of urban waste as a source of energy or materials, thereby conserving limited fossil energy and virgin materials resources. A related objective is to achieve energy conservation through reduced energy consumption in the processing of urban wastes. In pursuit of these objectives the projects of the UWT Branch focus on five specific areas. Three are technical process options, mechanical, thermal, and biological processes; the fourth is directed at nontechnical (e.g., institutional) aspects of implementation; and the fifth provides general program support.

The DOE's authorization for this effort is contained in the Department of Energy Authorization Act (1). This act expands DOE's scope of effort beyond the research, development, and demonstration (RD&D) functions authorized in the Federal Nonnuclear Research and Development Act (2). The DOE program in the field of resource recovery is coordinated with the U.S. Environmental Protection Agency's (EPA) and Department of Commerce's programs authorized under the Resource Conservation and Recovery Act (3). This combined federal effort is designed to ensure that wastes are managed in a manner that will protect public health and the environment and to conserve valuable material and fossil energy resources. Following a brief overview of activities in resource recovery, this paper will focus on the research, development, and demonstration activities of the UWT Branch of the DOE.

OVERVIEW

The recovery of energy and materials from waste in centralized processing plants is still in the early stages of commercial application (4). In 1977 less than 1% of the nation's total waste stream was being recovered. An important reason explaining this low level of recovery is that some of the necessary technologies are still in relatively early stages of demonstration and commercial application. Also, some technologies require further development before they will be ready for demonstration. Furthermore, those technologies being implemented need operating histories to document their technical and economic feasibility.

Figure 1 shows the range of technical RD&D options in resource recovery. Three broad technologies are available to recover energy and energy-intensive materials from urban wastes: mechanical, thermal and biological.

Mechanical processing separates wastes into various components including metals, glass, and a refuse derived fuel (RDF). Generally, a mechanical process is a preliminary step to the thermal and biological technologies. The metallic components,

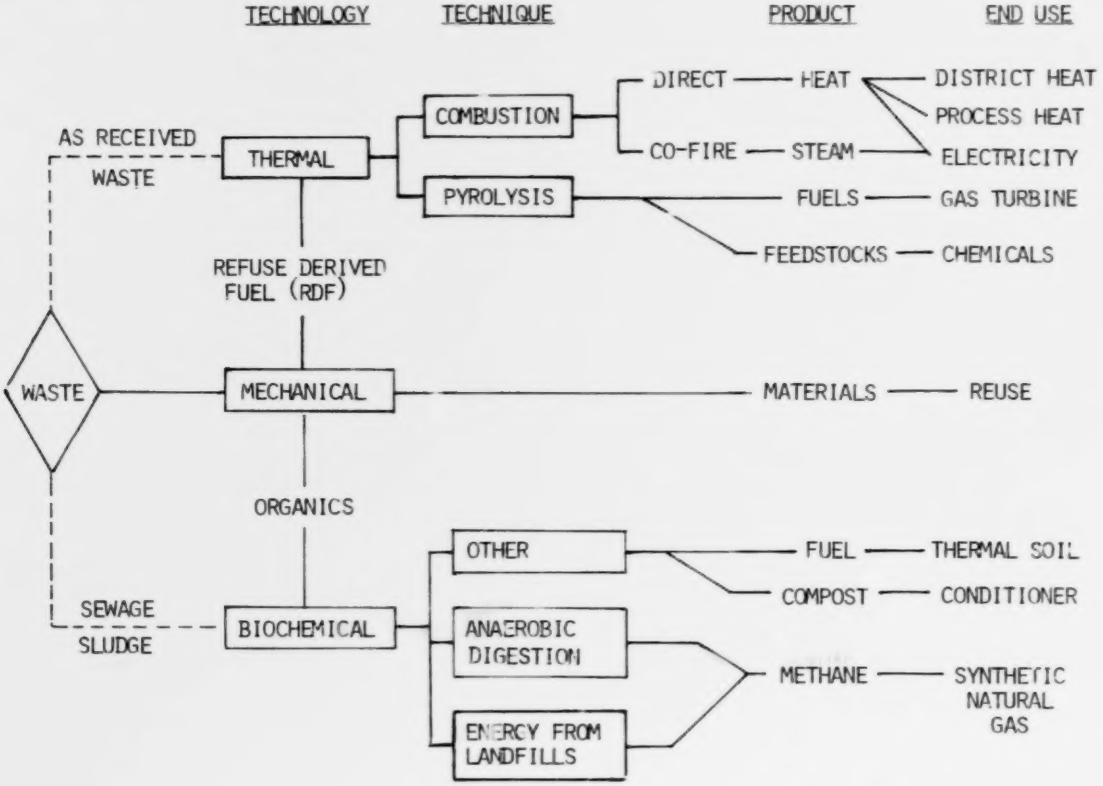

TECHNOLOGY
TECHNIQUE
PRODUCT
END USE
AS RECEIVED WASTE
THERMAL
COMBUSTION
PYROLYSIS
DIRECT
CO-FIRE
HEAT
STEAM
DISTRICT HEAT
PROCESS HEAT
ELECTRICITY
FUELS
GAS TURBINE
FEEDSTOCKS
CHEMICALS
REFUSE DERIVED FUEL (RDF)
WASTE
MECHANICAL
MATERIALS
REUSE
ORGANICS
OTHER
FUEL
THERMAL SOIL
COMPOST
CONDITIONER
SEWAGE SLUDGE
BIOCHEMICAL
ANAEROBIC DIGESTION
ENERGY FROM LANDFILLS
METHANE
SYNTHETIC NATURAL GAS

Fig. 1 Technical RD&D options

glass, and paper fibers are recycled to displace virgin materials.

In general, mechanical processes are employed for size reduction and separation by size, weight, shape, density, and other physical properties. A typical processing line would utilize shredding for size reduction of raw refuse, followed by some form of air classification to separate the particles into a light (organics) and a heavy (inorganics) material stream. The light fraction, without further processing, has generally come to be known as fluff RDF.

A demonstration unit sponsored by the EPA to produce RDF at St. Louis proved the basic feasibility of the mechanical separation processes, transport and storage techniques, and the combustion of fluff RDF to replace 5% to 27% of the pulverized coal used in suspension-fired utility boilers. However, the refinement of equipment components and the technical and economic optimization of the basic technology still requires a great deal of work.

There is one operating facility recovering and using fluff RDF on a daily basis. This facility has encountered a series of economic and technical problems. A second facility is entering its first year of production evaluation prior to finalization of fuel sales contracts. Several facilities are in a shakedown phase or under construction.

The preparation of densified RDF by pelletizing, briquetting, or extruding is now being explored and evaluated, and is particularly adapted for stoker and spreader-stoker furnaces. However, it has not been demonstrated commercially, and the costs, handling characteristics, and firing characteristics must yet be evaluated. The anticipated advantages of densified RDF are greatly improved storage and transportation characteristics.

The production of dust RDF (particles smaller than 0.15 millimeter) is being developed in a proprietary pilot-plant process. After adding an embrittling chemical, coarsely shredded waste is pulverized to a dust-like consistency. The resulting dust RDF has a higher Btu content than fluff RDF along with greater density, homogeneity and decreased moisture content. In addition, dust RDF may be capable of direct co-firing with fuel oils. However, the dust-like composition necessitates special handling to minimize the danger of an explosion.

A "wet" mechanical separation process utilizes hydrapulping technology adapted from the pulp and paper industry to reduce raw waste to more uniform size and consistency, followed by a centrifugal, liquid cyclone process for separating the pulped mass into light and heavy fraction. The original EPA sponsored pilot plant at Franklin, Ohio, is still operating although it no longer produces low grade fiber for a roofing felt plant as originally intended. After successful test burns of the 50% organics, 50% moisture pulp, a full scale facility designed to burn the pulp to recover steam is now under construction.

Ferrous metal recovery systems are the most advanced material recovery systems; paper fiber recovery by both wet pulping and dry processes has been demonstrated successfully, and aluminum and glass recovery has been demonstrated with limited success. Efforts are planned to improve system efficiencies in terms of energy use, quantity, and quality of material recovered.

Combustion techniques burn waste for the recovery of heat energy. Waterwall combustors are the most technically developed energy recovery systems and employ special grates to burn "as received" urban waste and recover steam either at saturated or superheated conditions. Over 250 plants are operating in Europe and Japan. There are seven plants operating in the United States, although three of these were originally constructed as incinerators. Only one plant has developed an effective steam marketing plan and six years after start-up, has begun steam sales. Worldwide, there have been a number of technical problems with the control of corrosion and erosion being the most serious. The most recent European designs have solved these problems but at an increased capital cost.

The more popular U.S. development seems to be the recovery of RDF for sale to coal-using facilities. With modifications, existing boilers can use RDF as a supplemental fuel. Most development has been aimed at the large suspension fired utility boiler and, while test burns have been encouraging, technical problems have developed. These are related to burning characteristics, slagging and environmental control equipment performance. All can be solved. However, upgrading control devices such as electrostatic precipitators will require significant increases in the capital costs of the system.

Another variation being demonstrated is the combustion of RDF in a dedicated boiler as a principal fuel. Normally the boiler is of spreader-stoker design with some consideration given to the use of fossil fuels such as high sulfur coal as a load leveler and steam production stabilizer.

The only available small-scale system is a packaged two chamber incinerator with waste heat recovery. This technique is practical at the 25 to 100 tons per day (TPD) scale. In these units partial oxidation occurs in the first section of the unit and causes a portion of the waste material to degrade and give off combustible gases. These gases, as well as products of combustion and particulate from the first chamber, flow to a second chamber where they are combusted with excess air and a natural gas or oil pilot flame. The combustion products then flow through appropriate heat transfer equipment to produce steam, hot water, or hot air. Four small cities and more than 60 industrial plants use the technique with heat recovery equipment today.

Thermal gasification and pyrolysis systems are also under development with several systems approaching the full scale demonstration stage. Specific discussion is not included on individual techniques since they are still in the developmental stages. Fuels from these processes include gases, oils and chars.

Biological techniques use living organisms to convert organics into useful energy forms. These processes are in the developmental stages. DOE is sponsoring an anaerobic digestion process that converts the organics in urban waste to methane under controlled conditions. This process is at the proof-of-concept stage and is not expected to be commercialized until the late 1980s. Another bioconversion process to recover methane gas from existing landfills is at or near commercialization. Because of the explosive nature of the gas, increasing attention has been paid to controlling the migration of the gas. Subsequently, the use of the gas for energy purposes developed. Today there is one operating site, two sites in development, one site under construction and 10 sites in an advanced planning stage to utilize the recovered gas. It is estimated that one trillion cubic feet of methane is potentially recoverable from existing landfills with 55 billion cubic feet of pipeline quality methane available yearly just from the 100 largest landfills.

Generally, the mechanical, thermal and biological resource recovery technologies can be ranked in order of their stages of development as shown in Table 1. The DOE RD&D program addresses all of these technologies as will be discussed in the next section.

Table 1. Developmental Stage of Resource Recovery Technologies

Level of Development	Technology
High	. Ferrous Metal Recovery
	. Anaerobic Digestion of Municipal Liquid Wastes
	. Waterwall and Modular Controlled Air Combustors
	. Coarse, Fluff, and Wet Pulped RDF
	. Paper Fiber Recovery
	. Landfill Gas Recovery
	. Glass, Aluminum and Other Nonferrous Metal Recovery
	. Dust and Densified RDF
	. Pyrolysis and Gasifiers
	. Anaerobic Digestion of Solid Waste
Low	. Enzymatic and Fungal Synthesis

Figure 2 shows the range of nontechnical RD&D options in resource recovery. Three broad categories are of concern: institutional, socioeconomic, and legal. All of these are interrelated with the solutions to nontechnical problems often more difficult to attain than those to technical problems.

Institutional issues are many and complex. Perhaps the principal issue is that cities are conservative, risk avoiders and politically are more concerned that their urban wastes disappear than they are with resource recovery. Additional problems involve waste stream control, difficulty of regionalizing waste processing, and to this point, lack of control of land disposal of wastes although regulations are now mandated and in development. The difficulty of obtaining new landfill sites, however, is a positive influence, particularly in more populated areas.

To be economically viable, waste to energy plants depend on two major sources of income: the sale of the energy product and a fee to dispose of waste in the plant (tipping fee). Additional income can be realized from the sale of recovered materials. Where landfill (tipping fees) or energy costs are high, waste based systems can compete with fossil fuels. Of the plants in operation only one enjoys economic success.

Furthermore, because of the high front-end costs and the risks associated with using a new technology, financing these facilities may be a problem, particularly for local government units. Marketing the energy and materials is essential for the economic viability of these technologies. However, many local governments do not have marketing expertise, and often, governments cannot legally enter into the long-term contracts that are essential for using

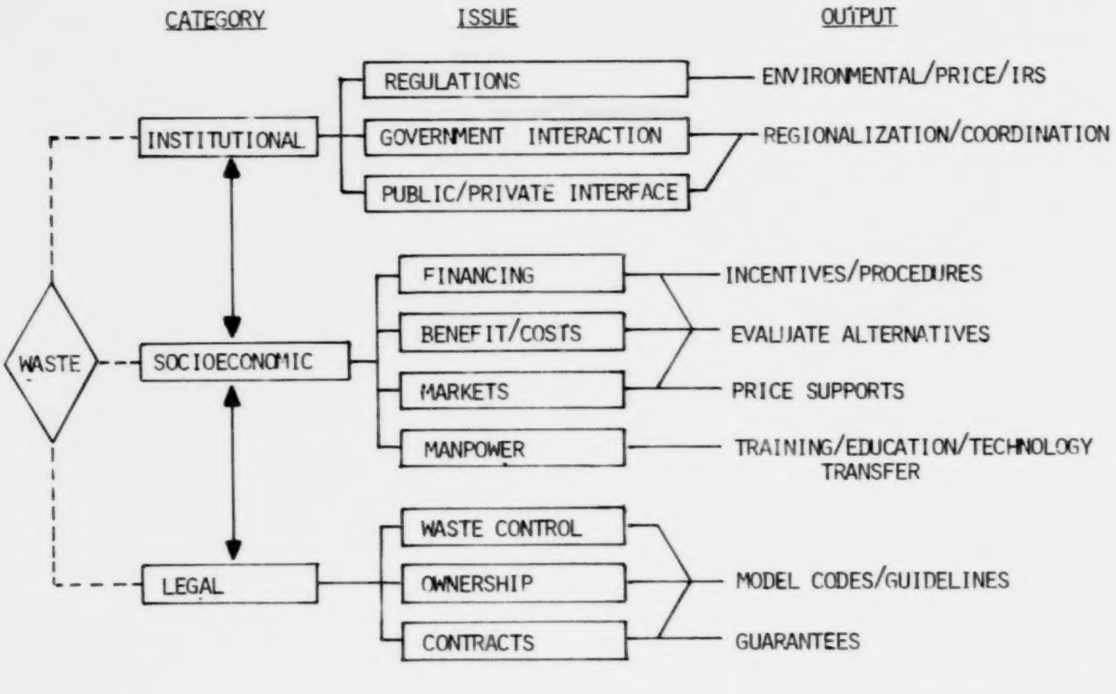

CATEGORY
ISSUE
OUTPUT
REGULATIONS
ENVIRONMENTAL/PRICE/IRS
INSTITUTIONAL
GOVERNMENT INTERACTION
REGIONALIZATION/COORDINATION
PUBLIC/PRIVATE INTERFACE
FINANCING
INCENTIVES/PROCEDURES
BENEFIT/COSTS
EVALUATE ALTERNATIVES
WASTE
SOCIOECONOMIC
MARKETS
PRICE SUPPORTS
MANPOWER
TRAINING/EDUCATION/TECHNOLOGY TRANSFER
WASTE CONTROL
LEGAL
OWNERSHIP
MODEL CODES/GUIDELINES
CONTRACTS
GUARANTEES

Fig. 2 Nontechnical RD&D options

these capital-intensive technologies. In addition, electric utilities, which potentially represent a large market for refuse derived fuel, do not have an economic incentive to use this fuel because of fuel-cost pass through provisions and contracted long-term fuel supplies.

Innovation has also occurred in the development of institutional arrangements to accomplish energy and materials recovery. These innovations range from the creation of statewide authorities (such as those in Connecticut and Delaware), which are charged with developing and implementing high priority projects, to formation of not-for-profit public corporations (such as the Nashville Thermal Transfer Corporation), which operate much like utilities. These state-wide and regional bodies have facilitated the organization of regional recovery facilities by reducing some of the complexities normally encountered in arriving at intermunicipal agreements. In addition, several different approaches have been used to bring together municipalities (the generators of waste), private industry (the suppliers of recovery technologies), and the energy and materials market (the buyers of recovered resources) as partners in joint efforts to accomplish the combined public purpose of energy conservation and waste disposal.

Several innovative approaches to project financing have been used. In response to local hesitancy or inability to issue general obligation bonds for recovery plants, various forms of revenue bond financing have been developed. These financing approaches have been extremely beneficial because they have forced project sponsors to thoroughly investigate the anticipated performance of proposed recovery systems, and to assure that project revenues are both secured and sufficient to cover all operating and debt service costs.

DOE activities in the nontechnical area are to assess economic, social, institutional and legal resource recovery barriers, and also to provide implementation guidance and direct technical and financial assistance to nonfederal entities, including state and local governments, and private enterprises.

The nontechnical RD&D program may include evaluations of public attitudes and institutional barriers to resource recovery, and performance of benefit/cost studies to evaluate the total social costs of resource recovery and disposal options including the cost of environmental damages and externalities such as balance of payments and national defense. In addition, the program may also include the development of the following: new markets for recovered resources, product specifications of recovered materials to enhance their marketability, methods to properly compare resource recovery with traditional waste disposal options, and methods to estimate the life cycle costs of resource recovery systems.

These RD&D efforts are being augmented by a diversified program of economic incentives, including grants, contracts, cooperative agreements, loans, loan guarantees, and price support. Currently, loan guarantee and price regulations are being developed. An active program of training, technical assistance and information transfer is also being initiated. This includes preparation of case studies, conducting workshops and seminars, and developing university and apprenticeship programs.

Although a significant effort is being made by DOE in the nontechnical area, the focus of this paper is on DOE activities in technology RD&D. The previous discussion of nontechnical concerns is included because this type of RD&D is often ignored or considered inconsequential. However, the need for innovation and research in the nontechnical area is more important than additional development of some technologies.

DOE TECHNOLOGY RD&D PROGRAM IN RESOURCE RECOVERY

The Urban Waste Technology Branch of DOE has, over the past few years, funded approximately 80 RD&D projects with about 60 still active. Figure 3 shows a rough distribution of funding, by percentage, for various types of efforts. Classifications of some projects are subjective and many projects have components that could be classified differently. Therefore, the distribution presented should be viewed as a general indication of the emphasis of DOE's past RD&D efforts in resource recovery.

In addition, this distribution represents only a narrow view of DOE's program. The program emphasis has been shifting as priorities change and advances are made in the state of the art. DOE has contracted with the MITRE Corporation to update its 1975 RD&D priority evaluation (5). This document will be used to develop future RD&D priorities for funding.

Future funding of research and development projects is expected to remain constant in real terms over the next few years, while funding for demonstration projects will increase significantly. This prediction is based on congressional support for demonstration projects as manifested in authorities granted DOE for loan guarantees for demonstration projects (6) and direct financial support for municipal demonstration projects (7).

With these caveates in mind, Figure 3 can be useful as a basis of discussion on the types of projects being funded by DOE. Specific examples are discussed below.

Mechanical Processes. Waste quantification and characterization studies, for the purposes of this paper, are classified as mechanical research and development projects. This was done, in part, because the sizing, separation, and benefaction functions of mechanical systems are often determined by the type and quantity of waste available.

The quantity of wastes generated is a function of, among other factors, producer packaging practices, consumer buying patterns, demographic and economic characteristics of a region, season of the year and day of the week. Proper measurement and estimation of wastes generated in a region would improve process selection and design decisions.

The composition of the waste will determine its energy content, pollution characteristics, and corrosion and abrasion potential. The types of wastes generated in an area affect the suitability of many processes for converting the wastes to energy. In addition, proper characterization of the waste can improve equipment design by providing basic data needed to evaluate equipment performance.

Standard practice has been to use either national-average per-capita waste generation rates and composition factors or costly and time consuming weighing and sorting procedures to estimate waste quantities and compositions. Improved estimating or measurement procedures are sought in a number of DOE R&D projects.

Franklin Associates is attempting to develop an improved procedure for estimating solid waste generation rates based on land-use zoning in a region. If successful, the land-use based waste generation factors would be almost as simple to use as national average factors but would result in estimates that are based on local demographic/economic development patterns.

Waste characterization is also an important component of most of the demonstration projects funded by DOE. Although innovative methods for characterizing waste are not being sought, the data produced and experiences gained will provide information that could improve these activities in the future.

The National Bureau of Standards (NBS), under sponsorship of DOE and EPA, began a study in 1977 to develop a method for measuring the gross caloric value of raw refuse and various types of RDF. In addition, the study is evaluating the moisture, ash, carbon, sulfur and chlorine characteristics of the waste samples. NBS is also evaluating the homogeneity and preparation required for bomb calorimetric experiments utilizing two bomb calorimeters with order of magnitude sizes such as 2.5 g and 25 g.

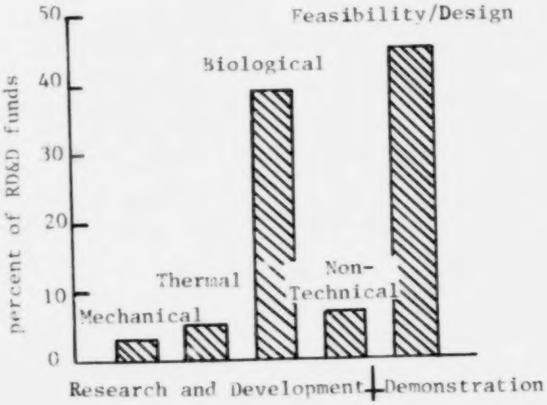


Fig. 3 UWT funding distribution

Results on a limited number of samples of Teledyne National Pellet and Combustion Equipment Associates ECOFUEL-II "demonstrated that RDF samples can be processed for bomb calorimetric experiments to produce results with a precision (standard deviation of a measurement) approximately equal to or better than 1%" (8). The heat value of the RDFs ranged between 25.20 and 21.93 MJ/kg (10,835 and 9427 Btu/lb). The ash and sulfur contents were about 12% and 1%, respectively. The degree of preparation required in order to obtain reproducible calorific results will be determined when concurrent tests are made with two sized calorimeters.

The National Center for Resource Recovery has been contracted to assemble and test various components of waste preprocessing equipment. Studies include ferrous and other material recovery, RDF preparation, removal of noncombustibles during pneumatic transport of RDF, energy recovery from air classified heavies, and development of a mobile RDF plant. Systems Technology Corporation (SYSTECH) has been contracted to test gas, mechanical and pump mixing, both separately and in combination, of a high solids concentration in an existing anaerobic digester. SYSTECH is also studying the performance characteristics of a coarse trommel in another project.

In addition, an innovative approach for size reductions and separation of solid waste, using a steam cannon similar to the technology used to make "puffed" foods, is being developed and tested by Burke, Davoud and Associates. Recently, tests using the steam connon on paper feedstock were conducted, and additional tests on other constituents of urban waste and mixed refuse are scheduled. Hydrolysis tests on samples of cannon discharges are being conducted by the U.S. Army Laboratory in Natick, Mass. A major objective of this effort is to determine the optimum cellulose particle size for cellulosic enzymatic hydrolyzation.

If this technique is successful, it could improve the economics, energy efficiency, and digestion efficiency of anaerobic digestion processes such as the one being tested in Pompano Beach, Florida.

A continual effort is expected to develop, improve and determine performance characteristics of waste preprocessing equipment. Efficient and effective waste preprocessing is required to optimize the performance of many resource recovery facilities.

Thermal Processes. The majority of thermal process projects involve the combustion of municipal wastewater sludges in combination with solid waste or alone to produce energy. Since these projects were recently awarded as part of two program research and development announcements, and consequently, are just being initiated, no results are available.

Two other thermal process projects being conducted by Battelle Columbus Laboratory and Stanford University are investigating the technical and economic viability of fluidized bed combustion of solid waste. Another study by Monsanto Research Corporation will be testing the combustion properties of an oil/refuse fuel prepared using a wet pulping process similar to the one used in Franklin, Ohio.

Although approximately 5% of the RD&D funds are devoted to research and development of thermal systems, the majority of the 28 demonstration projects funded by DOE (see Figure 4 for the locations of these demonstration projects) involve combustion systems such as waterwall incinerators, multi-chamber starved-air combustors and multi-hearth furnaces, or the projects will involve the production of an RDF for use in a dedicated boiler or cofired with coal. At least three of the projects are seriously considering the demonstration of a pyrolysis facility. The Dutchess County, New York, project has advanced to the engineering design stage and a full scale demonstration of the Union Carbide PUROX System may occur in the early 1980s.

Future research will focus on improving the operating characteristics of large-scale facilities, developing viable pyrolysis, gasifier and fluidized bed techniques, improving the handling, storage and combustion properties of RDF, developing and evaluating environmental controls for resource recovery facilities, and developing small-scale systems.

Biological Processes. The current DOE R&D program for biological processes consists of three interrelated program areas: anaerobic and enzymatic digestion of solid wastes and municipal sludges; production and conservation in wastewater and water treatment plants; and production and extraction of methane from sanitary landfills.

By far the largest share of DOE's R&D dollars have been allocated to anaerobic and enzymatic digestion projects. More than half of the biological processes R&D funds and about 20% of DOE's Urban Waste Technology RD&D funds over the last few years have gone to two major projects.

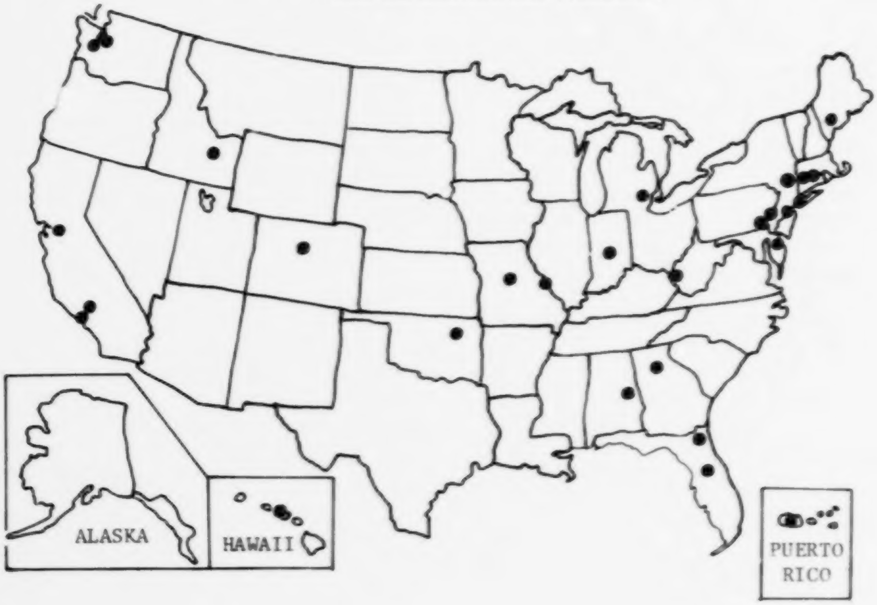
The first of these projects involving enzymatic hyrolysis has been ongoing since 1976 at the U.S. Army Natick Laboratory. The objective of this effort is to convert cellulose in urban wastes to glucose with further fermentation to alcohols and other energy products. Numerous biological projects should benefit from the information generated by this project. However, enzymatic hydrolysis is not expected to be an economically viable option for converting waste to energy or energy intensive products in the near future (9).

In 1977 the Energy Research and Development Administration funded Waste Management Corporation to design and build a proof-of-concept anaerobic digestion facility. The concept is based on laboratory investigation by Dr. John Pfeffer of the University of Illinois (10). The facility was built in Pompano Beach, Fla., and is referred to as the Refuse Conversion to Methane (RefCOM) project.

This experimental facility is designed for a capacity of 100 tons per day of raw refuse and is expected to produce 0.6 million cubic feet of gases (CH_4 and CO_2) per day. The objectives of the experimental program are to establish information on quality and quantity of the gas produced, establish optimum process operating parameters in both mesophilic and thermophilic modes, and evaluate the technical reliability of the technique.

Design and construction of the facility was completed in January, 1978, at a final cost of $3.6 million. Waste Management Corporation has been contracted by DOE (the UWT Branch assumed responsibility

DOE DEMONSTRATION PROJECTS



for the project when DOE was formed) to conduct a two to four year experimental program.

The RefCOM start-up program began in March 1978. Since that time Waste Management Corporation has been correcting a number of nagging mechanical problems primarily dealing with the front-end and digester feed systems (11). Some redesign and fabrication of these systems are being made. The experimental program will begin after the start-up problems have been solved.

DOE has a number of programs underway that support the RefCOM project. These include the digester mixing and steam cannon projects discussed previously and a project recently awarded to SYSTECH to analyze methods for recovering energy from the digester sludge.

Of the many anaerobic digestion projects underway, two are: (1) the design and construction of an anaerobic digester to convert fecal material and bedding from various cages, enclosures, runs, etc. in the Philadelphia Zoo to a medium Btu fuel gas and fertilizer; and (2) the development of a small-scale on-site energy system that incorporates wind energy, solar energy, and bioconversion of wastes to produce a storable fuel gas. The latter project is being conducted at California State University, Northridge, California.

DOE has an active program to promote energy production and conservation in wastewater and water treatment plants. The anaerobic digestion of sludges at municipal treatment plants is an established technology. The gases produced, however, are often flared resulting in lost energy. Furthermore, the energy consumption in water and wastewater treatment facilities is not known. Estimates varied from 0.25 to 1.0 quads in 1978.

Since 1976 Oak Ridge National Laboratory has been developing and analyzing a packed bed anaerobic digester, referred to as the ANFLOW pilot plant, that might reduce the cost of sewage treatment plants and the waste sludge disposal problem. The 5,000 gallon-per-day pilot plant is currently producing methane from sewage sludge. Tests at a commercial scale treatment plant with a 50,000 gallons per day capacity are planned for fiscal year 1979.

A laboratory and small pilot scale program to enhance anaerobic digestion by the addition of activated carbon is being conducted by the Battelle Pacific Northwest Laboratory. It was found that small quantities of activated carbon do not substantially enhance the production of methane in unstressed digestors. However, it does increase gas production in stressed digestors. (12)

In the area of energy production and conservation in water and wastewater treatment, DOE and EPA are funding a number of joint ventures. For example, they have a contract with Hittman Associates to prepare an energy assessment procedure manual. The manual will provide guidance to planners, design engineers, plant operators, federal agencies and other interested parties for energy recovery and conservation in the design, construction and operation of municipal wastewater collection and treatment facilities.

Another project, being conducted by the Reedy Creek Improvement District in Florida, is evaluating the use of water hyacinth in an advanced wastewater treatment lagoon to remove nutrients from the water in an energy efficient manner. Future efforts may evaluate the feasibility of harvesting the hyacinth periodically and anaerobically digesting it to produce a fuel gas and a fertilizer. The EPA and DOE are also assessing the energy conservation aspects of a solar assisted wastewater treatment plant in Wilton, Maine. In the future, DOE efforts in the area of energy production and conservation in wastewater and water treatment plants will probably involve more joint ventures with the EPA.

The DOE effort in energy generation, extraction and utilization from sanitary landfills began in March, 1978, with a symposium in Laurel, Md., on the utilization of methane generated in landfills. The symposium provided one of "the first opportunities for everyone doing work related to the utilization of landfill methane to meet and exchange information" (13). A second symposium on landfills is scheduled for March, 1979.

In July, 1978, DOE/UWT issued a program research and development announcement for the development and analysis of alternative techniques to utilize combustible gas produced in existing sanitary landfills. Three projects were selected for funding as a result of this solicitation.

The Los Angeles County Sanitary District was funded to evaluate and implement a system to provide landfill gas (40-50% CH_4) to Rio Hondo College located near the Puente Hills landfill (14). The gas is expected to replace the interruptible portion of the college's present natural gas requirements. The project includes a boiler conversion study to determine the practicality and cost of adapting the boilers to use the landfill gas. A gas delivery criteria to ensure proper performance of the modified boiler will be established. If either the modification costs exceed the estimated benefits or the gas delivery criteria can not be satisfied, the project will be terminated. Information generated from the study concerning the use of landfill gas as a substitute for interrupted natural gas is expected to have widespread value.

Pacific Gas and Electric Company (PG&E) was selected to conduct a comprehensive analysis of the gas stream and all condensates from the City of Mountain View's landfill (15). The purpose of the investigation is to obtain information on the potential sources of corrosion caused by landfill gas and to foster acceptance of the use of landfill gas by industry. Air intrusion will be evaluated for the major components (i.e., nitrogen and oxygen) and the potential for CO_2 utilization from landfill gas will be evaluated. The PG&E project is significant because it addresses many generic issues and problems that have been limiting the use of landfill gas.

The New York State Energy Research and Development Authority was selected to design, develop, install and operate gas engine generation equipment to demonstrate direct use of the landfill gas for supplying electricity (16). The electricity will be used by several New York City Department of Sanitation facilities including the maintenance building, tractor repair shop, and roadway lighting. The data collected will identify and focus on problem areas in gas recovery and utilization. This demonstration at the Fresh Hills site on Staten Island will also provide information on life cycle operation of the associated system components, the reliability of gas supply, the corrosive nature of the gas, and the feasibility of large-scale landfill-gas-electricity projects.

In addition to these three projects, two of DOE's demonstration projects deal with the extraction and use of landfill gas. Adams County and Commerce City in Colorado will be designing a facility to recover methane from a network of sanitary landfills as an energy source for several local industries, and Lochman and Associates will be designing a system to recover methane from landfills to generate electricity in Glendale, Calif.

All of these programs focus on the use of landfill gas as a boiler fuel without upgrading. The gas is used in a boiler as a substitute for natural gas or to produce electricity. These projects are designed to foster the use of landfill gas in the near future.

In the long run, however, improved methods and procedures are needed to optimize the generation of gas, improve drilling, collection and upgrading practices and technologies, and devise economic and safe ways to store and transport the recovered gas. This must be done in an environmentally acceptable manner and result in competitively priced products.

Toward these program goals a second competitive solicitation in the area of optimizing gas production will be issued by Argonne National Laboratory early in 1979. In addition, Johns Hopkins Applied Physics Laboratory is preparing a workbook that will address all the technical, institutional, environmental, and legal issues associated with methane recovery from sanitary landfills. The workbook will also describe the experiences of the approximately 14 landfill sites actively considering or implementing landfill gas recovery programs.

Future methane from landfill RD&D will be directed at major technical and nontechnical problems. The level of funding and its direction will, in part, depend on the findings of current DOE and other programs.

SUMMARY

Although all of DOE's projects in the field of resource recovery from urban wastes could not be discussed in this paper an attempt to demonstrate the breadth and depth of the DOE/UWT program through selected examples of RD&D activities was made. Both technical and nontechnical RD&D activities are being carried out to foster the improvement and implementation of mechanical, thermal and biological processes for reprocessing urban waste into energy and materials.

The DOE/UWT program is coordinated with EPA and other federal, state and local efforts to ensure the development of an effective and comprehensive national program to recover the energy and material currently being discarded as waste. If this program is successful, approximately 3% of the nation's energy needs could be supplied by reprocessed wastes.

REFERENCES

1. Department of Energy Authorization Act of 1978 -- Civilian Application, Public Law 95-238, February 1978.

2. Federal Nonnuclear Research and Development Act of 1974, Public Law 93-577, December 1974.

3. Resource Conservation and Recovery Act of 1976, Public Law 94-580, October 1976.

4. From (often verbatum) unpublished planning document prepared by Urban Waste Technology Branch of DOE, Urban Waste Technology Program at Argonne National Laboratory, and DSI Resource Systems Group, Boston, Mass.

5. MITRE Corp., Energy Conservation Waste Utilization Research and Development Plan, July 1975.

6. Department of Energy Authorization Act of 1978 -- Civilian Application, Public Law 95-238, Title II - General Provisions, Section 19-Loan Guarantees for Alternative Fuel Demonstration Facilities, February 1978.

7. Department of Energy Authorization Act of 1978 -- Civilian Application, Public Law 95-238, Title IV-Establishment of Financial Support Program for Municipal Waste Reprocessing Demonstration Facilities, February 1978.

8. Kirkland, D.R., et al., Summary of 1977 Fiscal Year Efforts to Establish Test Procedures for the Determination of the Gross Calorific Value of Refuse and Refuse-Derived-Fuels by Oxygen Bomb Calorimetry, National Bureau of Standards, Draft Report, 1978.

9. Spano, L.A., Enzymatic Hydrolysis of Cellulose to Glucose, Quarterly Reports, U.S. Army Natick Research and Development Command, Natick, Mass.

10. Pfeffer, J.T., and J.C. Liebman, Energy from Refuse by Bioconversion, Fermentation, and Residue Disposal Processes, Resource Recovery and Conservation, Vol. 1, pp. 295-313, 1976, and Biological Conversion of Organic Refuse to Methane, Vol. I and II, Final Report No. ERDA/NSR/RANN/SE/AER 73-07872/FR/76/4, Department of Civil Engineering, University of Illinois, November 1976.

11. Waste Management, Inc., RefCOM - Status Report Covering the Start-Up Phase, March 15 - October 1978. To be published.

12. Ahlstrom, S.B., and R.R. Spencer, Assessment of Powdered Activated Carbon Addition to Anaerobic Digestion at Salt Lake City, Utah, Pacific Northwest Laboratory, Richland, Wash., April 1978, and monthly progress reports submitted to DOE/UWT.

13. Proceedings of a Symposium on the Utilization of Methane Generated in Landfills, sponsored by U.S. Department of Energy, hosted by Applied Physics Laboratory, The Johns Hopkins University, Laurel, Md., March 1978.

14. Proposed Delivery of Puente Hills Landfill Gas to Rio Hondo College, proposal submitted to the DOE in response to PRDA #EM-78-D-01-5153 by the Los Angeles County Sanitary District, August 1978.

15. Utilization of Landfill Gas from City of Mountain View, proposal submitted to the DOE in response to PRDA #EM-78-D-01-5153 by Pacific Gas and Electric Company, August 1978.

16. Landfill Gas-To-Electricity Conversion Project, proposal submitted in response to PRDA #EM-78-D-01-5153 by New York State Energy Research and Development Authority, August 1978.

Dr. Cohen manages the Urban Waste Technology program at Argonne National Laboratory, which has provided technical support to DOE's Urban Waste Technology Branch during the past year. This paper reflects his understanding of the DOE/UWT program and does not necessarily reflect the opinions and policies of DOE.

SOLID WASTE DISPOSAL RESEARCH ACTIVITIES OF THE FEDERAL GOVERNMENT IN CANADA

H. Mooij, P. Eng.
Waste Management Branch
Environmental Impact Control Directorate
Environmental Protection Service
Environment Canada
Ottawa, Ontario
K1A 1C8

ABSTRACT

In Canada the Federal government's role is principally to develop solid waste management technology, to generate and evaluate technical solid waste management information, and to develop new or improved guidelines or codes of good practice relating to various waste management aspects. These activities are conducted on a national basis for the benefit of the industry and regulatory agencies.

Solid waste research activities in Canada are being undertaken primarily at the federal government level. Current research activities, relating to land disposal in particular, are underway in each of the following study areas: landfill leachate research; municipal waste disposal site selection; landfill field investigations; co-disposal studies; landfill gas research; and the NATO/CCMS landfill project. This paper describes Environment Canada's current research projects in these areas of interest.

INTRODUCTION

Solid waste research activities in Canada are being undertaken mainly at the federal level of government, but also at the provincial government level, in order to come to grips with the problems facing both the private sector and the regulatory agencies. Some provincial governments are actively contracting out basic research studies or undertaking similar in-house investigations, although most others are simply studying localized problems of disposal or local potentials for resource and energy conservation. The bulk of the research effort in Canada is undertaken by the federal Department of the Environment (Environment Canada).

The Waste Management Branch of Environment Canada is very active in the resource conservation and the municipal and industrial waste management areas of responsibility. However, the constraints of this presentation do not permit a complete disclosure of all our activities. Therefore, I have chosen the focus of this presentation to be the activities of our Branch relating to the disposal of wastes onto land.

These activities will be briefly described under the following headings:

1. landfill leachate research;
2. municipal waste disposal site selection;
3. landfill field investigations;
4. co-disposal studies;
5. landfill gas research; and,
6. the NATO/CCMS landfill project.

LANDFILL LEACHATE RESEARCH

Leachate Production

Although a significant amount of research work has been accomplished to date on the subject of leachate generation, or production, at municipal solid waste landfills, there are still many basic questions left unanswered about the actual process of leaching. Leachate production is generally an estimated variable, and never really measured directly at a landfill site.

The ability to predict leachate quantity and quality is probably the most necessary feature required for the design of leachate control systems, including natural attenuation and leachate treatment systems. All landfill leachate control systems design work relies heavily on an accurate input function describing the leaching behavior of the landfill. An estimate is only as good as the "rule-of-thumb" used, and therefore, we have initiated an attempt to develop a simple solid waste leaching model at the University of British Columbia in Vancouver.

A good quantative, descriptive and predictive model of the leaching of solid waste landfills and of the mechanisms associated with the leaching process may be important to assess the environmental impact of leachate on receiving waters; to aid in the design of any required leachate treatment facilities; to provide estimates of the material inputs into an underlying groundwater system as a first step in determining leachate concentration there; and, to assess the likely effects of co-disposal of various liquid and/or semi-solid waste in landfills. For the initial stages of this work a model was chosen which assumes a simple physical process to describe the leaching. The initial model assumes flow-through of infiltrating water and a mass transfer of soluble materials from the solid phase to the liquid phase due to a concentration difference driving force, as well as connection within the liquid phase. The model has been tested for the simple case of plug flow starting at the top surface of landfill, with a constant rate of infiltration, insignificant moisture in the refuse, and a univorm distribution of leachable materials.

This model provided leachate concentrations as a function of time. The calculations require values for the refuse depth, the rate of infiltration, refuse field capacity, and three empirically determined parameters. The model has been fitted to data from solid waste lysimeter experiments for six contaminant curves and a range of operating conditions. The calculated curves and corresponding data curves generally showed a good correlation when the empirical parameters were suitable adjusted.

The model is currently being further modified to provide both the quantity and quality of leachate as a function of time, and for various patterns of infiltration and fluid flow. Other variables being ested are various landfill operational parameters. A final report on the initial work should be available within the next few months. Leachate Control and Treatment Infiltration into disposed refuse results in the production of leachate which is recognized to be potentially hazardous to the environment. There are a significant number of documented case histories which show that the uncontrolled migration of leachate from improperly located waste disposal sites can result in extensive groundwater and/or surface water pollution. These case histories have been used to demonstrate the need for the design of leachate control and treatment systems at waste disposal sites.

There is a growing trend in regulatory agencies insisting on some degree of leachate control including collection and treatment. This trend is disconcerting in that many leachate control systems have not been proven technically, while others have simply been designed to expedite the approvals process. Furthermore, some systems may be failing because of inadequate design or improper installation, whereas others are being over-designed without due regard to the cost-effectiveness of the systems. Rarely has the environmental benefit and the complete cost and benefit of such a system been evaluated.

Landfill designers, researchers, and regulatory agencies have become concerned with problems relating to proper selection, design, and operation of leachate control and treatment systems. There is a recognized need to develop practical criteria for the design and operation of such leachate management systems.

In response to this need, the Waste Management Branch and its contractors sponsored two international round-table discussions on the topics of leachate control, held in Vancouver, and leachate treatment, held in Halifax.

The session on leachate control considered the topics of natural and engineered controls to minimize leachate production, collect leachate on-site, recirculate leachate, and rectify leachate migration problems through aquifer manipulation as a control procedure. A report is being prepared on the recommended procedures for leachate control based on a concensus by technical experts from the U.S. and Canada.

The purpose of the leachate treatment session was to discuss and document current treatment concepts, practices, and methodologies.

Attendees at this session included recognized treatment experts from Canada, the U.S., Germany and Norway. A report is being prepared to document the discussion on the need for and the factors affecting leachate treatment; the treatment of leachate in the natural hydrogeologic environment; biological treatment systems physical-chemical treatment systems; and, the concensus of expert opinion expressed at the session.

With regards to in-situ attenuation, it was recognized that there is a difficulty in designing for the use of the natural setting as an attenuation and/or treatment system, and although it was agreed that the assimilative capacity of the hydrogeologic environment for leachate contaminants is quite significant, ground water contamination will usually result.

The concern, therefore, must be with the degree of contamination which will be allowed, and whether such contamination actually constitutes pollution.

It was recognized that all constructed treatment systems require, prior to design, the setting of an effluent quality standard. Similarly, if the hydrogeologic environment is to be designed to accept a leachate loading, water quality standards at a finite distance downgradient from the base of the disposal area must be established. Most commonly, the maintenance of drinking water standards has been used as a criterion for leachate discharge in the hydrogeologic environment.

A realistic leachate discharge objective would be that leachate must not impair a reasonable, legitimate, present or potential off-site groundwater use. The principal problem which makes it difficult to define an effluent standard for the discharge of leachate to the hydrogeologic environment, is that in general, the hydrogeologic environment cannot be improved to allow for an upgrading of the standard if necessary. At a treatment facility, such an upgrading can readily be facilitated.

It coule be argued that all landfill designs, where leachate is discharged to the hydrogeologic environment, should be equipped with contingency plans which are designed to control the discharge of leachate to this environment should it be required. If a contingency plan can successfully be implemented, a setting of design standards could be readily done.

With respect to engineered treatment systems, it was agreed that current processes can produce effluent liquids virtually free of contaminants, notwithstanding the high costs involved. However, at the same time, rather than being destroyed or converted to a less objectionable form, the contaminants are either retained in a highly concentrated residual stream or transferred to another medium, both of which require disposal.

Most treatment processes have as their objective, the production of a high quality effluent liquid without regard for the residual stream. Since landfills are frequently the last step in disposal, simply transferring leachate contaminants from one form to another for disposal "elsewhere" was not considered to be a satisfactory solution to a leachate problem.

Many solid waste disposal systems are not presently in a position to finance "best available technology".

Consequently, it is hoped that, for cases where leachate treatment is clearly deemed necessary, it will be done according to the "most practicable technologh" after consideration of all relevant factors has been completed. This should be based on realistic assessment of the potential of, and expectations for, the disposal area, be it a surface or a groundwater system, and the resources at hand to solve the problem.

Reports on both the control and treatment sessions will be available soon.

Extensive research into leachate treatment has been underway for the last few years at the University of British Columbia, and an in-depth reporting of this program will be presented later in this symposium by Dr. Don Mavinic of their Civil Engineering Department.

Leachate Toxicity

At the third annual research symposium in St. Louis, I briefly mentioned our work in developing a rapid leachate toxicity testing procedure. The procedure, using rainbow trout fingerlings in stoppered BOD bottles, proved satisfactory for many test situations.

Toxicity has often been suggested as a valuable indicator parameter in surface waters monitoring programs. However, standard bioassay procedures are expensive and generally require large volumes of effluent, and may take up to three days per sample. The rapid toxicity procedure was developed to overcome these problems, and it was demonstrated to be a less expensive, valuable in-situ monitoring procedure.

A final report on the set-up and use of the procedure has been published.

Our continuing interests in leachate toxicity led us to develop an even simpler test using Daphnia, and an attemp to attribute leachate toxicity to concentrations of specific leachate contaminants. In addition, work was done to determine p^H effects on toxicity, and to assess the effects of landfill operating variables such as rainfall, sludge additions, and elapsed time since disposal, on leachate toxicity.

Equations were developed by statistical regression analyses of the experimental data to relate toxicity to contaminant concentrations. It was found that the relationship between toxicity and contaminant concentrations can best be expressed in terms of the un-ionized ammonia concentrations as well as the concentration of zinc in the case with the Daphnia test, or the copper concentrations in the case with fish tests.

Furthermore, it was reported that the adjustment of p^H in test procedures can dramatically reduce the toxicity of a given sample.

A final report is in preparation.

MUNICIPAL WASTE DISPOSAL SITE SELECTION

Accepting that landfilling will be a requirement for many years to come, it is necessary that technology required to locate and manage these sites be developed to a high degree.

Over the past year we have been continuing our development of a selection procedure for locating suitable landfill sites which could be used to service small communities. The procedure will be a simple, yet comprehensive attemp to provide a small community with a decision making process which will assis them in locating the most suitable site from an environmental, a public protection, and an operation and management point of view, without having to rely on outside expertise. A "cook book" approach is being used in preparing a final report on the procedure.

The selection procedure works as follows Potential sites are evaluated against environmental protection criteria, including distance requirements to property boundaries based on acceptable attenuation distances within the local soil environment, distance requirements to downgradient water wells, and distance requirements to ensure protection of nearby dwellings from landfill gas migration problems. Other criteria also apply.

A pass-fail test is used for each criteria. Failure to pass any of the criteria would render the site unsuitable without special site engineering.

From a public protection point of view, the major criteria of importance in addition to environmental and health criteria are aesthetics, traffic, land use designations and site completion. The operation and management criteria ensure the selection of the most operable and cost-effective location.

The procedure is based partially on a variety of procedures documented to date, and should prove to be a simple, yet effective decision tool for decision makers in small communities.

The procedure should be finally available within the next few months.

LANDFILL FIELD INVESTIGATIONS

Although a great deal of research has already been devoted to landfill technology, the long and inconclusive arguments between experts over the acceptability of particular sites clearly points to the need for additional basic technical information. These arguments are most often prevalent at public meetings or regulatory hearings where frequently neither side of the argument can be adequately supported by firm technical information.

In spite of the large amount of research which has already been conducted, problems arise as a result of the difficulty in showing the applicability of laboratory data to field conditions and in the difficulty in studying the processes directly in the heterogeneous hydrogeologic environments of the real world.

Because a large amount of detailed information has already been gathered at the C.F.B. Borden landfill, as reported in previous years, this site offered us an excellent opportunity for further investigating both the applicability of laboratory data for making field predictions and for the field investigation of contaminant migration and attenuation processes.

Several activities have been undertaken, and will be continuing, at this landfill site. One such activity includes the further definition of the physical hydrogeology by supplementing information from our past studies with some continuous core sample analysis for detailed stratigraphy, point dilution testing for direct velocity measurements, single well response tests for determining in-situ K values, and field dispersivity measurements.

Other activities at the site have included the geochemical surveying of the contaminant plume through field measurements of Eh, p^H, DO and specific conductance taken on samples extracted from multi-level sampling devices.

Trace metal-oxide coating studies are also being undertaken to determine the contribution to contaminant levels in the downgradient soils due to the release of trace metals from soil oxide coatings being dissolved under reducing conditions. Studies have shown that the bulk of the trace element content of contaminated groundwater may be derived not from the waste material itself, but from the natural manganese and ferric oxide coatings on the surrounding material through which the leachate moves. Another part of the field studies consists of the evaluation of the degree of anaerobic decomposition of leachate organics migrating through saturated soils under anaerobic conditions. Initial results have shown a COD reduction of 86% after 1.5 meters of travel and a TOC reduction over the same distance of 90%.

A comprehensive modelling exercise completes the long list of activities being undertaken at the Borden landfill. The development of a calibrated flow model is being followed by a simulation of the distribution of a non-reactive solute, namely chloride, and then a reactive species. Lastly, the effects of transient flow conditions will be examined.

One important aspect of this modelling exercise is to determine a suitable input function for the contaminant release from the landfill itself. In the absence of historical data from the site, a successful leaching model such as the one being developed at the University of British Columbia may provide necessary information.

If modelling is to have a place at all in our future work, such as has been suggested by Weston in their report to EPA on "Pollution Prediction Techniques for Waste Disposal Siting", then the Borden work should be the "proof of the pudding".

CO-DISPOSAL STUDIES

Septic Tank Sludge and Municipal Refuse

Our previous research project, on the effect of adding septic tank pumpings to refuse has been completed. The general finding of this research was that the addition of septic tank pumpings, in sufficient quantity, significantly reduced the mass of contaminants discharged, and particularly heavy metals, when compared with a control containing no pumpings. This effect, attributed largely to biological activity, was reduced when rainfall rates were increased from 15 in (381 mm) to 45 in (1143 mm) per year. Increased gas production and a greater initial percentage of methane gas combined with reduced contaminant mass discharges at the high septic tank pumping loading rates made this technique look promising from both an environmental and an energy recovery viewpoint. Before proceeding with a large scale operation, however, it was felt necessary to determine whether or not the tie up of metals was permanent or simply transient in nature.

It was decided, therefore, to continue to apply water to the existing 9 lysimeters at the rates which had been previously used, and to analyze gas and leachates on a continuing monthly basis.

Railfall applications and leachate collection have been continued since the termination of the original contract, and with only three exceptions, all leachate contaminant concentrations have continued to decrease. The exceptions are one tank which showed increase in colour but no other increases; another tank showed an anamalous steady increase in iron concentration; and yet another showed an initial increase in iron contrentation but then a drop to the previous low level. Generally, p^H has increased. Concentrations of metals such as cadmium and lead decreased to below detection limits for all tanks, and ammonia nitrogen also decreased below detection limits for most tanks.

There is presently no indication that desorption of contaminants is occurring. However, a continued increase in gas production in some tanks shows that biological activity is continuing, and if biological activity is the mechanism which is causing metal tie-ups, this indicates that desorption may not occur for some tiem yet, if at all.

A final report should be available this summer, 1979.

Metal Sludges and Municipal Refuse

Having demonstrated the beneficial effects of adding untreated biological sludge to landfills in terms of achieving metal tie-ups, we decided to undertake further work to determine whether or not these previously found beneficial effects would apply when industrial sludges were added to the refuse as well.

A series of thirteen lysimeters were constructed using 12 inch diameter PVC pipe. Flat bottoms were welded to each and specially designed sealed tops were constructed. The necessary additions of septic tank sludge and an arsenic containing waste and an electro-plating sludge were each determined based on past co-disposal experience.

The tanks were filled and put into operation in August 1978. Results to date are still being analyzed, and the study will continue into 1981.

LANDFILL GAS RESEARCH

Gas Production and Migration

The objective of our gas production and migration study is to provide information about gas composition, pressure, and production in landfills. Such information is essential for both an analysis of gas migration into adjacent soils and an assessment of gas recovery potentials at landfill sites. This study, to be discussed in detail later in this program by Dr. Grahame Farquhar of the University of Waterloo, will also involve the use of field data in the calibration of a previouslu developed gas transport model. The calibrated model will be used to display variations in gas migration patterns and to evaluate various gas control and recovery schemes.

Gas Recovery and Utilization

Although it is being recognized that a municipal solid waste landfill may be a significant energy source, it is clearly not feasible to tap smaller sites in remote locations for low BTU content gas supplies for consumption elsewhere. Unfortunately, there is usually no nearby gas distribution system available. Even if a pipeline could be found next to every small site, the economics of cleaning the gas to pipeline quality could be prohibitive.

Our study addresses the possibility of extracting landfill gases year round at any site and using these gases for an on-site energy supply. One market which could readily benefit in Canada from such a readily available supply is the energy intensive greenhouse industry, which presently faces fuel costs of up to

$30,000 per year per greenhouse acre.

California studies have suggested that the best economics lie in the direct use of the gas on-site with minimal gas processing and refining. Our 10 month study is intended to demonstrate the use of the collected gas to supply the energy requirements of a small greenhouse throughout the year. It is planned to grow tomatoes in this greenhouse situated on a completed site in St. Thomas, Ontario.

The completed St. Thomas Landfill Site is divided into two sections. The section under study was in operation from 1967 to 1978. This section is comprised of approximately 24 acres of refuse with an average depth of 40 feet. The gas production wells, the gas monitoring and pressure probes, and the various greenhouse facilities.

The gas production well consists of a 36 inch augered bore hole, logged as 1 foot of fill, 28 feet of refuse and 3 feet of native soil. A 6 inch diameter PVC pipe with an attached 8 feet of stainless steel well screen (50 slot) was placed in the center of the augered hole. The hole was then backfilled with pea gravel, with gas pressure and monitoring probes inserted at various depths. The top of the gas production well was closed using 1 ½ feet of 36 inch diameter concrete tile. Bentonite was placed around the tile and a concrete plug was used ar the surface. A concrete cap is placed on top of the concrete tile.

A rubber adapter is being used to connect the pipe leading from the gas pump to the concrete cap, so as to allow pumping directly off the gravel pack to permit an assessment of the feasibility of pumping off such an inexpensive gravel pack without having to install gas extraction well hardware. After completion of pumping from the gravel pack, 6 inch PVC pipe will be connected directly to the gas line feeding the gas pump.

The gas recovery system extracts the gas from the production well, passes the gas through a water knock-out drum and either pumps the gas to a furnace within the greenhouse or exhausts the gas to the atmosphere.

The control on the gas system will be a pressure release valve. The pump will run continuously at a set flow rate, and if teh pressure goes up in the line, the pressure release valve will allow gases to exit to the air. When the furnace is not in operation, all the gas will be released to the air.

A forced air furnaces has been adapted to utilize methane gas. A back-up electric furnace willbe installed in case of system failure, to prevent crop damage due to frost.

A total of 46 gas monitoring and pressure probes were installed. In addition, 3 gas monitoring and pressure probes were installed within the gas production well, and 4 gas monitoring probes were installed below the greenhouse liner to monitor for gases coming from the fill underneath the greenhouse.

The complete system is currently in operation, and methane concentration and pressure distributions within the landfill, changing as a result of varying pumping rates, are being monitored.

The study will be completed in August, 1979 and a final report should be available shortly thereafter.

NATO/CCMS LANDFILL PROJECT

A major international effort is underway among the member countries of NATO, including the U.S. and Canada. The purpose of the pilot project id to study hazardous wastes management, and one part of this project is a landfill study being supported by the U.S., Canada, Norway, the U.K., the Netherlands, and teh Federal Republic of Germany. The purpose of the landfilling study is to assess the role of landfilling in hazardous waste disposal. As Chairman of this sub-project for the next three years, I will be reporting on our deliberations and coordinating input from the various landfill research programs being undertaken by each participating country. All submissions will be used to prepare a final project report to NATO.

The results of our work should have a significant impact on policy planning within the member countries.

One of the topics to be addressed will be the the co-disposal of industrial and municipal refuse. Member countries at present appear to have opposing view points on the merits of co-disposal, and teh resolution of this issue, if at all possible on the basis of research results, should prove to be a most interesting challenge.

Another very important aspect of our joint international undertaking is the expressed desire by some member countries to pursue future research efforts on a cooperative basis and to establish a formal information exchange.

In accordance with this spirit of developing cooperative international efforts we have already initiated a coordination with the Solid and Hazardous Waste Research Division of the EPA of our respective landfill gas research studies, in the hope that we can mutually benefit from each other's work from the outset, and avoid costly duplication. It may even be possible to directly tie into similar German studies now getting underway. The benefits of such an international coordination of efforts will obviously accrue to us all.

The landfill sub-project will be completed in late 1980.

PILOT SCALE PROCESSING EQUIPMENT EVALUATIONS FOR RESOURCE RECOVERY

Dr. Harvey Alter
National Center for Resource Recovery, Inc.
Washington, D.C. 20036

ABSTRACT

A pilot scale (ca. 20 tph) pilot plant for investigating the mechanical processing of municipal solid waste had been established by the National Center for Resource Recovery. Its scope was expanded, and its use developed, under a grant from SHWRL-MERL, U.S. Environmental Protection Agency. The purpose was to investigate particular aspects of the processing for the recovery of products to specification for reuse. The intent was not to exhaustively prove or demonstrate operating parameters, but rather to obtain data useful to designers and implementors, so as to reduce perceived risks of this form of processing and technology transfer. The pilot plant is described; experimental results pertaining to investigations of upgrading refuse-derived fuel by screening prior to air classification, aluminum recovery and jigging preparatory to glass recovery, are presented.

SCOPE AND OBJECTIVES

The processing of mixed, municipal solid wastes for the recovery of useable and saleable materials, and for the preparation of a refuse-derived fuel, usually employs equipment and unit operations common in other industries. In spite of this "technology transfer," there is little documentation of the performance or utility of the borrowed devices to assist designers in adopting them for processing wastes. One reason is that the output product from one type of unit operation is often needed as the input feed to another. It is difficult to investigate unit operations singly; a continuous plant, or nearly so, is required.

Starting early 1974, the National Center for Resource Recovery began to assemble equipment for a continuous pilot plant so as to investigate the performance of some particular unit operations. Once assembled, the effort was supported by several grants from the Environmental Protection Agency (1-4).

The overall objective of the experimental work was to record aspects of the performance of materials recovery unit operations to assist designers and implementors of resource recovery. It was not the objective to rigorously prove or establish operating parameters for the unit operations but to obtain sufficient data to guide future systems' design and to reduce the perceived risks of the technology. This paper summarizes some of the findings to give a broad overview of the type and nature of the experimental work. It does not include all findings and detail nor reports at all on: the performance of prototype air classifiers, devices for pneumatic removal of ash components in RDF, cleaning the recovered aluminum product, nor the performance of most of the equipment in the glass recovery circuit. The interested reader is referred to other publications and the project final report cited in the text.

THE FACILITY AND PROCESS FLOW

The work was conducted at the National Center's Equipment Test and Evaluation Facility (ETEF) in the District of Columbia, located in what was the oversize bulky waste processing area of the District of Columbia's operating incinerator. In 1974, an agreement was signed which permitted use of part of the building and some of the equipment for experimental purposes.

Packer trucks were diverted from the incinerator tipping floor, as needed, to provide feedstock for investigations. Unrecovered materials, or samples after use, were disposed of in the incinerator pit.

The oversize bulky waste processing area originally consisted of a tipping area and steel pan conveyors feeding a horizontal hammermill. The District permitted temporary modifications of the facility so that it could evolve into a pilot plant for resource recovery investigations. The capacity of the shredder, by itself, is probably of the order of 100 tph. However, the infeed and outfeed conveyors originally installed were intended for bulky waste, of higher bulk density than packer truck refuse. Consequently, the capacity of the system with packer truck refuse was no more than about 20 tph.

The modifications permitted allowed installation of many different unit operations. In most instances, there was a severe space restriction and equipment had to be installed and located in areas and configurations that were far from optimum. The specific arrangements were dictated by the available space and did not resemble any attempt at an engineered plant. Only packer truck refuse collected in residential neighborhoods was used for the work described in this report. The description below omits that portion of the facility which was used for processing the light fraction into densified refuse-derived fuel, described elsewhere (4).

The process flow is shown in Figure 1. The municipal solid waste (MSW) was first size-reduced in shredder (1); the particle size distribution of this material has been reported (5). In a late configuration, the shredded MSW was screened at (2) to remove particulate inorganic material as a means of investigating the upgrading of the fuel product. Screen (2) also acted as a vibratory feeder to the air classifier (3). Several different air classifiers were investigated and are described in Reference (6).

The light fraction from the air classifier was de-entrained in cyclone (4). In early configurations, when screen (2) was not used, screen (5) was employed as a means of investigating the removal of inorganic fines from the light fraction. The dust and air effluent from the cyclone (4) were discharged into a large settling chamber when it was discovered early that the effluent contained many small pieces of paper, approximately 1 cm^2 in size. The settling chamber was a blocked-off, unused small room, fitted with fabric filters over the door. Periodically, the room was cleaned out. In the course of some investigations of air classification, the air discharge from cyclone (4) was recycled back into the air classifier.

Cyclone (4) discharged through a rotary air lock into a pneumatic conveyor so that the light fraction could be delivered to feeder-screen (5) and onto further processing. A small cyclone was placed over screen (5).

The heavy fraction from the air classifier passed under the magnetic belt separator (6), then past a magnetic head pulley (7) to make certain all (or nearly all) of the magnetic metals were removed and recovered. The remainder of the material was screened through a rotary screen (8) and separated into three fractions.

The fraction smaller than 5 cm from (8) was screened again at (10), a 1.2 cm vibrating flat deck screen. The oversize was rejected and the undersize fed to the Bendelari jig (11). The jig washed out the organic contaminants and the inorganic materials were sent to the crusher (12), operated in conjunction with 20 mesh screen (13) to reduce all of the material smaller than 20 mesh. Not shown is the 6.4 mm screen operated in series with screen (13) so as to remove non-crushable materials, principally small pieces of metal.

The underflow from screen (13) discharged into a sump and was pumped, as a slurry, into hydrocyclone (14) which discharged into froth flotation cells (15). The float product from (15) overflowed into spiral classifier (16) and was then screw-conveyed into the oil-fired dryer (17). The glass recovery circuit is described in greater detail later.

The oversize fraction from rotary screen (8), a material larger than 10.2 cm, was discharged as waste. The middling from (8) dropped on a vibratory pan feeder and was transported on a belt passing through the eddy current separator (9) for aluminum recovery.

After (9), the material was discharged as a waste.

Equipment Description

Much of the equipment used is described in Table 1. The glass recovery equipment is described in a later section.

SCREENING OF SHREDDED MSW AS A MEANS OF UPGRADING RDF

Shredded MSW contains crushed rock, glass, sand and other similar small particulate inorganic materials. When air classified, the particulate materials are likely to be included with the light fraction. The light fraction is a common form of refuse-derived fuel (RDF) and the inorganic particulates add to the ash (noncombustible) portion. If the small particulates could be removed before air classification, the ash content of the fuel would be decreased, the heating value (as-received) increased, and the value of the fuel enhanced. The particulate material contains crushed glass. If the resource recovery plant includes glass recovery, the process flow should not permit the glass to be wasted in the air classifier light fraction.

In 1977, when an experimental vertical zig-zag air classifier was installed, it was decided to use a vibratory feeder as the means of providing an even feed of shredded MSW to the classifier. The feeder had a perforated bottom plate so that it acted as a vibratory screen, thus permitting investigation of the screening of shredded MSW as a means of reducing the content of removable inorganic fines (RIF) in RDF.

Background

The air classifiers used at ETEF were operated between about 8.6 and 25 m/s (1700 and 4900 fpm) air velocity. This may be compared to published values for the settling velocity of quartz powder (7); with a specific gravity of 2.65, quartz is similar to sand and glass. Based on this comparison, particles as large as 10 mm may be carried in the air stream at operating air velocities, consistent with the computations of Fan (8).

For the work described below, the experimental zig-zag air classifier was operated between 9 and 16 m/s to achieve between a 50/50 and 70/30 split, light/heavy fraction. The feed for these trials was the oversize fraction from the screen described below. If the material were not screened, Fan's work predicts that at 15 m/s (≈3000 fpm) inorganic particles 3 mm and smaller will be included in the light fraction. Also, the light fraction will contain 10 wt.% of RIF, close to operating experience. For example, previously reported particle size distributions of shredded MSW and accompanying air classifier light and heavy fractions (3), show a larger fraction of material passing 6.4 mm for the light fraction than for the heavy. Also, light fraction prepared in an air classifier operating at the upper part of the velocity range was found to contain 14 wt.% RIF. Most of this was in the particle size range less than 10 mesh (2 mm).

The performances of a screen is dependent on many design and operating factors, some controllable, others not. Further, methods of determining and expressing screen efficiency are not uniformly established (9). The method chosen here is to express performances as the efficiency of recovery, R, of the <6.44 mm fraction from the shredded MSW feed: $R = 100\ (f - t)/[f(1 - t)]$, where f is the wt. fraction of <6.4 mm material in the feed and t correspondingly in the oversize (10).

The feeder-screen was a Texas Shaker provided by Triple/S Dynamics Co. It had a total operating area 2.1 x 4.9 m (7 x 16 ft). However, not all of the area could be used as a screen in as much as there had to be an air seal between the air classifier feed point and the screen to prevent back leakage of air through the screening medium. The area actually used was measured as 2.1 x 2.4 m (7 x 8 ft).

The screening surface was 10 gauge steel punch-plate with 6.4 mm diameter circular holes on 1.1 cm staggered centers. The actual open area of this type screen is 48% (11). The screen surface was declined at 8° so the unit would fit the available space. There was no adjustment. The vibratory action was provided by a 5.6 kW (7-1/2 hp) motor with a V-belt drive to produce 20 c/s at an amplitude of 19 mm. The screen was fitted with rubber balls and a tray.

Results

Particle Size Distribution of the Feed. The particle size distribution of the shredded MSW feed at ETEF had been measured and fitted to a Rosin-Rammler function (5), predicting that 30.4 wt.% of the oversize fraction to the screen is <6.4 mm, verified by measurement. The average of the 10 determinations was 30.4% with a coefficient of variation of 28.4%.

Undersize Fraction in the Oversize. Samples of feeder-screen oversize product were collected and the weight fraction of <6.4 mm material remaining in each was determined (t). The samples were taken at different feedrates. The results are listed in Table 2.

Recovery Efficiency. The recovery efficiency, R, was calculated as above to over the range of feedrates investigated. For these calculations, f = 0.304 and t is determined. The computed values of R are also listed in Table 2.

Composition of the Screen Undersize. The feeder-screen undersize fraction contains inorganic particulate material and some organic materials, which appear to be residues of food and yard wastes. In order to determine the amount of inorganic material, the loss on ignition of the screen undersize was measured. The average of 14 samples, collected on eight separate days, was 82.6 wt.% inorganic material with a coefficient of variation of 8.92%. This confirms that the screen is removing mostly inorganic or ash-forming material before it can enter the air classifier.

The small amount of organic material included in the screen undersize fraction represents a potential loss of fuel, which can be calculated not to exceed 4.7% (6).

Scaling and Sizing of Screens

The results reported here can be used to estimate the size of a screen for a full-scale resource recovery plant. There are several ways of scaling screens. However, with the limited data available, a simple approach is taken.

Gaudin (12) states the capacity of vibrating screens to be from 5 to 20 t/ft^2-mm aperture - 24 h for ores. Assuming the ratio of densities of shredded MSW to ore to be 1/10, and screen capacity is proportional to this ratio, the "rated" capacity of the 5.1 m^2 (56 ft^2) screen used in this work is from 0.18 to 0.73 tph of shredded MSW (short tons).

The relation between recovery, R%, and the feedrate, F tph, is represented by (6), $R = 63.6/F^{0.42}$, or that R = 72.6% at F = 0.73 tph. A properly operated vibrating screen should have R = 90% or greater at R = 90%, F = 0.44 tph. Using the Gaudin scale law, F = 0.44 is the capacity of the screen. Following Gaudin, the scaling factor can be calculated (for R = 90%) as 1.2t(MSW)/ft^2-mm aperture -24h. Thus, a similar screen for 50 tph resource recovery plant would have an area of 6350 ft^2. Vibrating screens are usually designed to have a length twice the width (10) so this screen would be sized 17 x 34 m (56 x 112 ft), obviously too large for common sense.

Several design parameters could be changed to improve the screening efficiency, thus changing the size of the screen. For example, the 6.4 mm punch-plate used has an open area of only 47.8%. Screen cloth with a square hole of the same size

Table 2. Recovery of <6.4 mm Fraction by the Feeder-Screen for f=0.304, F= Short Tons/hr., t=Short Tons, R=% Recovery

Feedrate*, F	t	R
1.8 tph	0.180	49.7%
2.4	.192	45.6
3.7	.214	37.7
4.6	.230	31.6
6.1	.237	28.9
11.6	.250	23.7

---

*F in U.S. short tons

has an open area of from 60 to 69%, depending on the wire size. If the screening surface were so changed, the size of the screen for 50 tph would be reduced to 14.3 x 28.6 m (47 x 94 ft), still too large for common sense. Other changes in screen design, such as angle of decline and vibration intensity, are not likely to change the scaled dimensions significantly.

Other design features were considered in order to improve the efficiency of such a screen. The conclusion was that a flat screen is not suitable for the purpose, probably because the paper-like or flat nature of shredded MSW, causing it to lie flat on the screen and block the apertures (6). A rotary screen may be more suited, as proposed (13).

ALUMINUM RECOVERY USING AN EDDY CURRENT SEPARATOR

MSW may contain from 0.2 to 1 wt.% aluminum depending on whether or not aluminum beverage containers are marketed in the area. When the percentage approaches 1%, about 1/2 of this typically would be cans. The remainder would be foil, pie plates, castings, extrusions, and from miscellaneous sources. The alloy (chemical) composition of these different items may vary widely and the value of recovered aluminum depends on its alloy composition resembling or matching a standard alloy composition. Thus, there is advantage recovering the aluminum canstock in MSW in a pure form, to be processed back into aluminum suitable for reuse in wrought products such as cans. Recovered Al has high value.

Test runs were conducted using the Combustion Power Co. Al Mag 20 Eddy Current Separator. As will be shown, the results indicate that the Al Mag 20 is capable of handling feedrates and making reasonable to good separations well in excess of its design capacity of 1 tph. The Al Mag feed is the 10.2 x 5.1 cm fraction of the nonmagnetic portion of the air classifier heavy fraction. The product is not clean aluminum, but a mixture of alloys, some other nonferrous metals, and miscellaneous organic materials. This section deals only with the recovery of a mixed Al product using this eddy current device. Cleanup of the product to a market specification is described elsewhere (2,6). The eddy current separator has been described (14).

The procedure was to feed the Al Mag with heavy fraction that had previously been magnetically scalped and sized. For the test trials, whole aluminum cans were introduced into the heavy fraction along with the shredded aluminum canstock that was "native" to the feed. After magnetic separation, the feed was screened into a small trommel to produce a 10.2 x 5.1 cm fraction which concentrated the aluminum. The mass balance has been reported (2).

Experimental Results

Two series of experimental trials were conducted. The first was according to the process flow of Figure 1. The results led to the conclusion that the 10.2 x 5.1 cm trommel was undersized, hence inefficient.

In the second series, the middling product from the trommel was collected and screened a second time. The second series is referred to as "double-screen" feedstock.

Some of the experimental results are plotted in Figure 2 to 5. Figure 2 is a plot of the amount of organic contamination in the Al Mag product as a function of the feedrate for the single-screen feed. These results should be compared to Figure 3, a similar plot for the double-screened feed, illustrating the effect of the undersized trommel. (A trend line is shown to guide the readers.)

Figure 4 is a plot of aluminum can recovery efficiency as a function of feedrate for whole cans, combining results from using both single-screened and double-screened feeds. Figure 5 is a similar plot for shredded cans, again showing a trend line.

Discussion. The particular eddy current separator used was designed for a throughput of about 1 tph. The results indicate this device is capable of recovering 90% or so of whole cans when operated at feedrates in excess of four times this design figure, and of recovering about 65% of shredded cans when operated at design capacity. The recovery efficiency falls off greatly for shredded cans as design capacity is exceeded.

The performance is summarized in Table 3 reporting average values of some of the

Table 3

Summary of Al Mag Performance
at Feedrate up to 2 tph

	Metals in Feed, %	Metals in Product, %	Metals in Residue, %	Recovery Whole cans	Recovery Shredded cans	Residue as % of Feed
Single Screen	12.7	78.9	4.1	92.7	72.6	88.2
Double Screen	16.0	92.7	7.9	97.0	52.8	83.2

parameters for feedrates between 0 and 2 tph. This range is chosen to illustrate some points.

The 10 x 5 cm feedstock to the Al Mag contained 13 to 16% metal. The Al Mag concentrated this metal about five times at a recovery efficiency in excess of 90% for whole cans and 53 and 73% for shredded cans. The lower recovery rate for the double-screened feed is not understood. Note that more than 70% of the Al Mag feed is residue. The residue contains on the order of 4 to 8% metal, which is lost to disposal.

The tentative specification for recovered aluminum permits 2 wt.% organic contaminants. The average contents of organic contaminants at feedrates up to 2 tph was 8.5% using double-screen feed. Even the product from using double-screen feed at throughputs greater than about 1 tph contained more organic material than permitted by the specification. These results indicate a clean-up step is required to recover aluminum to specification. Some experiments with a double-pass of material through the eddy current separator, and with prototype clean-up devices (air knife and air table) have been described (6).

THE RECOVERY OF GLASS

Description of the Glass Recovery Facility

A froth flotation process to recover container quality glass from municipal solid waste was investigated; the process flow is shown in Figure 6. The feedstock was produced by screening a mixture of the air classifier heavy fraction (without magnetic metals), and the underflow of the feeder-screen to the air classifier.

There are several possible froth flotation processes depending on the particular choice of equipment and its arrangement. In each, the basic objectives are the same-to clean and size the feed to froth flotation cells, float the glass from the waste and contaminants, and dry the glass. There have to be intermediate steps of screening, pumping, and adding and subtracting water. One particular equipment arrangement was chosen to do this work described here, based on some "best judgement" estimates, the few available literature reports, laboratory work done as part of the National Center's internal research program, and conversations with people in the field. The process flow chosen was not believed to be optimum, but rather a starting point for further investigation. Indeed, several features of the process were incorporated so as to be able to investigate a particular feature, or option, compared to what may have been described by others.

The Process Flow and Associated Equipment. The process flow is shown in Figure 6. Each Glass Recovery Unit Operation (GRUO) is numbered. The numbers refer to the equipment list and description in Table 4 which summarizes each function.

The equipment was installed for what was believed to be continuous operation. Experience indicated this expectation was optimistic. For example, a large barrier to continuous operation was the absence of large surge capacities between the processing steps as the means of evening the flow of materials. This is particularly important in resource recovery processing where the composition of the input waste is temporal, hence the input feedrate to glass recovery uncontrollable, even if the remainder of the plant operates at all times.

The function of each piece of equipment, and the mass balance for the assembly, have been described (6). In the interest of brevity, only one portion of the plant is described here - the jig.

The purpose of the jig is to wash and separate a concentrate of stones and glass from the feed as one product, a mixture of nonferrous metals as another, and a waste fraction of the organic materials (e.g., food and yard waste) as another. It was anticipated that nonferrous metals would be recovered as a by-product of preparing the feedstock for glass recovery and that small pieces of such metal would accumulate as oversize material on the sizing circuit screen, GRUO 1.5. The amount of such metal separated this way was minor, probably because little is smaller than 1.2 cm.

Jigging is an essential, if not critical step in glass recovery, compared to other pieces of equipment which might be expected to operate more closely to experience in the minerals beneficiation industry. Once the jig has performed its function, the feedstock is similar to the inorganic mixtures common to other applications of froth flotation.

THE USE OF A JIG TO PREPARE GLASS FEEDSTOCK FOR RECOVERY

The feed to the jig is a mixture of glass, stones, metal, wood, food waste, and other organic materials. A mineral jig is not necessarily the only type of equipment which could be used for this purpose, but is well suited to the purpose.

"Jigging" action applies a principle called hindered settling (15,16), the reaction of particles to movement in relation to the medium surrounding them. The medium may be air, water, or some other fluid. All of the descriptions in this report refer to water as the jigging medium. Figure 7 shows a Bendelari jig, the type used for the work reported here.

The length of jig stroke is selected to cause the jigging medium to exceed the minimum velocity necessary to liberate the largest and heaviest particles, V_m. This velocity can be calculated for spherical (or near-spherical) particles (17) according to: $V_m = 26.32 \sqrt{D(S-1)}$ ... where: V_m = velocity (mm/s), D = maximum particle diameter (mm), and S = specific gravity of the material to be separated.

The largest and heaviest particles likely to be separated are nonferrous metals, approximately 12 mm in size, ranging down to glass and stones, <12 mm. The specific gravity of the metals might be as high as 9 (e.g., Cu, ignoring an occasional piece of Pb) and certainly not lower than 2.

The velocity of the water in the jig used ranged from 23 to 240 mm/s depending on operating factors, or that the jig used was capable of achieving the minimum velocity to separate the largest and heaviest particles likely to be found in the feed. Other operating factors have been discussed (6).

Description of the Jig Feed

The feed to the jig is the underflow from the 13 mm screen, GRUO 1.0, Figure 6. Measurement of the particle size distribution showed that >95 wt.% was ≤10 mm.

Table 5 gives the materials balance. From this, and the particle size distributions, it is possible to compute that about 94 wt.% of the total glass, sand, rock ceramic fraction (and all of the <6.4 mm underflow from the feeder-screen) are included in the <13 mm fraction.

Performance Requirements for the Jig

The suitability and function of the jig must be assessed in terms of its product yield and quality. The specification for the final recovered glass product dictates, in part, a performance specification for the jig. The recovered glass must be essentially free of organic materials (0.2 wt.% max.) and metals (0.05 wt.% max. Fe and 0.1 wt.% max. other), judging from the proposed specification (18).

Broken glass, obtained from a nearby recycling center, was used as ragging. Ragging for this purpose is essential and the pieces should not be flat, like broken glass, but spherical and/or small.

Experimental Results

During operation, samples of feed, hutch and cup product were taken and tested for particle size, composition and content of organic materials. Additionally, the jig table overflow was sampled and examined for glass and nonferrous metals carryover. Mass balances were determined. Table 6 tabulates some physical characteristics of the jig products as well as giving the mass balance (drained weights). The content of organic material was determined by measuring the loss on ignition (LOI). The results in Table 6 show the content of organic material of the cup product is 5.6 wt.% and the hutch product 0.17 wt.%. These results indicate the jig is capable of reducing the content of organic material down to the specification level required for glass or that elaborate separation steps beyond the jig are not needed. Further, the particle size distribution of the hutch product is such that approximately 60 wt.% is <1 mm in size, or approximately the required 20 mesh for froth flotation, which reduces the load on the impact (or other type) crushing mill.

The mass balance indicates that if the cup product was discarded, i.e., not used as part of the feed to froth flotation, there would be a loss of approximately 17% of feed, not necessarily of glass. If the cup and hutch products are combined, the loading of organic materials to the float cells is increased from 0.17 (for just the hutch product) to about 1.1% (for the combined product), assuming no subsequent losses of organic materials in the sizing circuit. Combining the two products, therefore, requires a dispersion float (or other step) to reduce the 1.1 wt.% to <0.2 wt.% organic content.

FUNDING ACKNOWLEDGEMENT

The work reported here was conducted under Grant R803901 from the Solid and Hazardous Waste Research Laboratory, Municipal Environmental Research Laboratory, U.S. Environmental Protection Agency, Donald Oberacker, Project Officer

REFERENCES

1. Alter, H., S. L. Natof, K. L. Woodruff, W. L. Freyberger and E. L. Michaels, 1974. Classification and concentration of municipal solid waste. Proceedings, Fourth Mineral Waste Utilization Symposium. E. Aleshin, ed. IIT Res. Inst. & U.S. Bu. Mines, Chicago, pp. 70-6.

2. Alter, H., S. L. Natof and L. C. Blayden, 1976. Pilot studies processing MSW and recovery of aluminum using an eddy current separator. Proceedings, Fifth Mineral Waste Utilization Symposium. E. Aleshin, ed. IIT Res. Inst. & U.S. Bu. Mines, Chicago, pp. 161-8.

3. Alter, H. and B. Crawford, 1976. Materials recovery processing research. A summary of investigations. Report on Contract 67-01-2944. U.S. Environmental Protection Agency, Washington, D.C., 99 pp.

4. Alter, H. and J. Arnold, 1978. Preparation of densified refuse-derived fuel on a pilot scale. Proceedings, Sixth Mineral Waste Utilization Symposium. IIT Res. Inst. & U.S. Bu. Mines, Chicago. in press.

5. Stratton, F. E. and H. Alter, 1978. Application of bond theory to solid waste shredding. J. Environ. Engr. Div., ASCE. Vol. 104: 93-107.

6. Alter, H., ed., 1978. Materials recovery from municipal solid waste: Investigation of air classification, upgrading RDF, aluminum and glass recovery. Grant R803901. U.S. Environmental Protection Agency, Cincinnati. Final Report in press.

7. Taggart, A. F., 1927. Handbook of mineral dressing. J. Wiley & Sons, New York, p. 9-02.

8. Fan, D. N., 1975. On the air classified light fraction of shredded municipal solid waste. Composition and physical characteristics. Resource Recovery & Conservation. Vol. 1: 141-50.

9. Taggart, A. F. *op. cit.*, p. 7-04.

10. *ibid.*, pp. 19-191.

11. *ibid.*, pp. 7-14.

12. Gaudin, A. M., 1939. Principles of mineral dressing. McGraw Hill, New York, p. 162.

13. Savage, G. and G. J. Trezek, 1976. Screening shredded municipal solid waste. Compost Science, pp. 7-11.

14. Abert, J. G., 1977. Aluminum recovery. A status report. NCRR Bulletin, Vol. VII, Nos. 2 & 3.

15. Richards, R. H., 1903. Ore dressing. Engineering & Mining J. Vol. 1, p. 636.

16. Gaudin, A. M. *op. cit.*, p. 250.

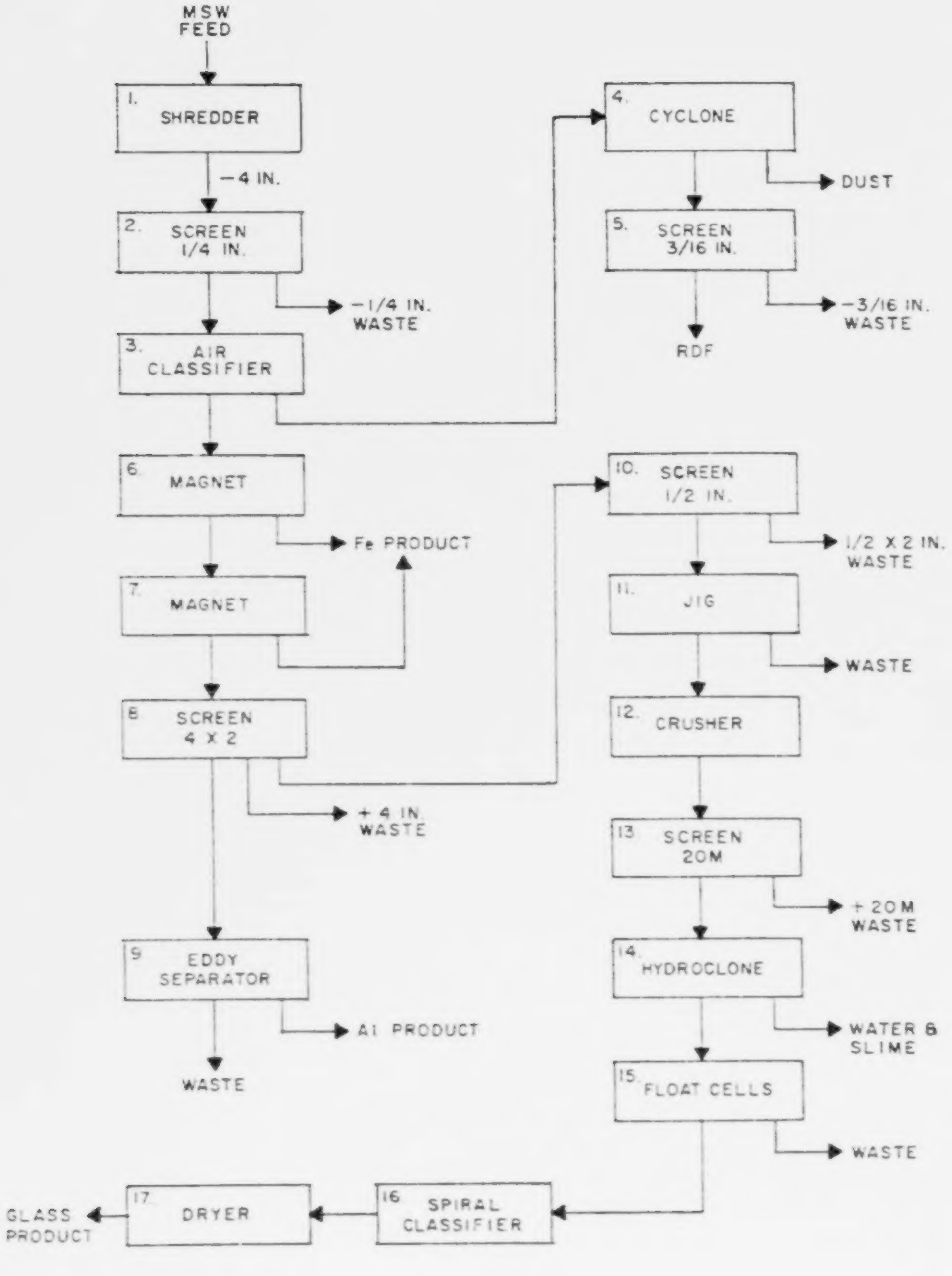
17. Richards, . H. and C. E. Locke, 1940. Textbook of ore dressing. McGraw Hill, New York, pp. 197-8.

18. Alter, H., 1979. Development of specifications for recycled materials. Conservation & Recycling. Vol. 2. in press.

ACKNOWLEDGEMENTS

Acknowledgement with thanks is made to the District of Columbia, Department of Environmental Services, for the use of equipment and facilities. Thanks are given to the various manufacturers who loaned additional equipment. The work described here is the result of the contributions and hard work of many staff members of the National Center and engineering co-op students who didn't mind an unusual assignment early in their careers.

Figure 1. Schematic of ETEF Process Flow


MSW FEED
1. SHREDDER
-4 IN.
2. SCREEN 1/4 IN.
-1/4 IN. WASTE
3. AIR CLASSIFIER
4. CYCLONE
DUST
5. SCREEN 3/16 IN.
-3/16 IN. WASTE
RDF
6. MAGNET
Fe PRODUCT
7. MAGNET
8. SCREEN 4 X 2
+ 4 IN. WASTE
9. EDDY SEPARATOR
Al PRODUCT
WASTE
10. SCREEN 1/2 IN.
1/2 X 2 IN. WASTE
11. JIG
WASTE
12. CRUSHER
13. SCREEN 20M
+ 20M WASTE
14. HYDROCLONE
WATER & SLIME
15. FLOAT CELLS
WASTE
16. SPIRAL CLASSIFIER
17. DRYER
GLASS PRODUCT

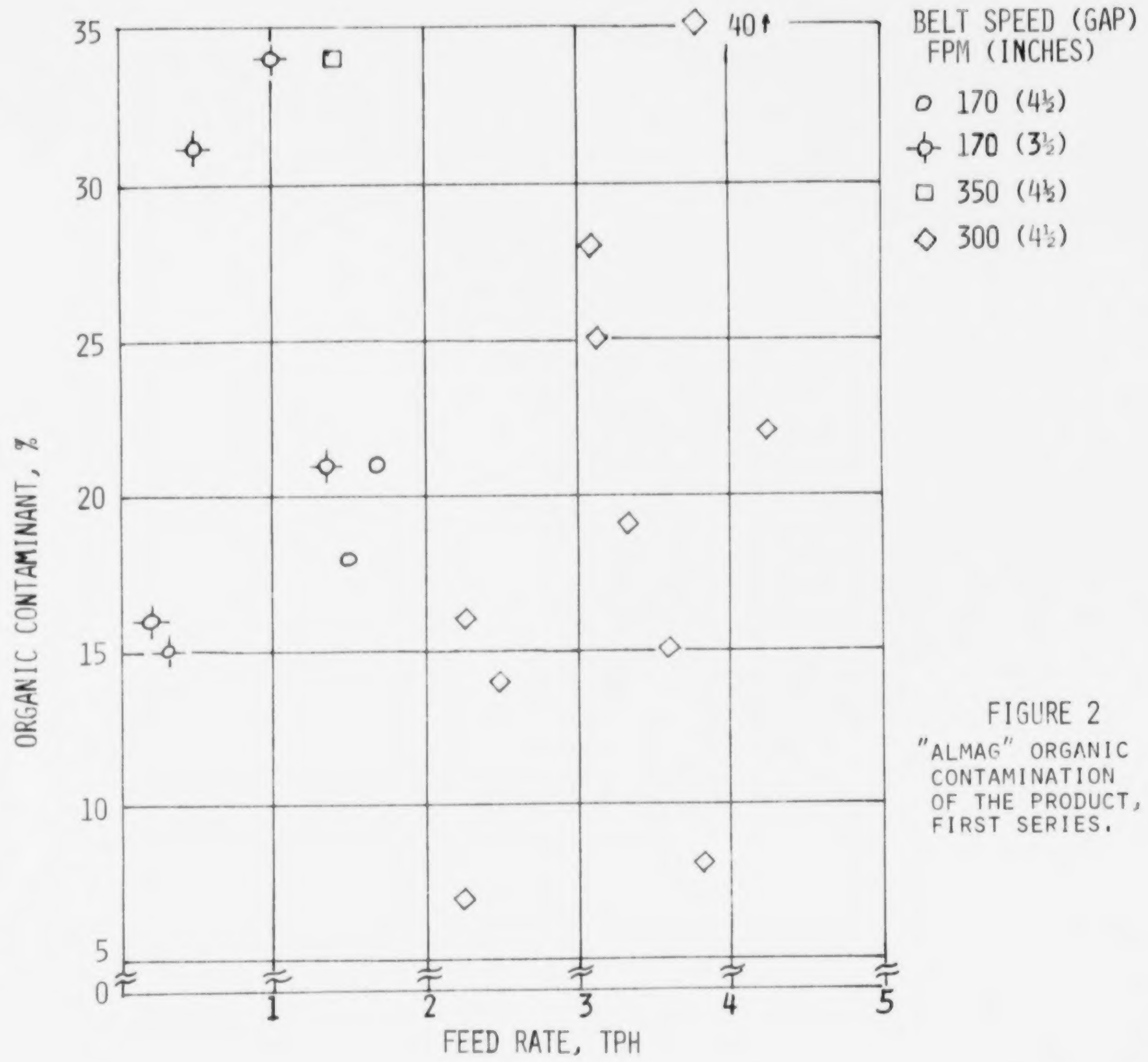


FIGURE 2
"ALMAG" ORGANIC CONTAMINATION OF THE PRODUCT, FIRST SERIES.

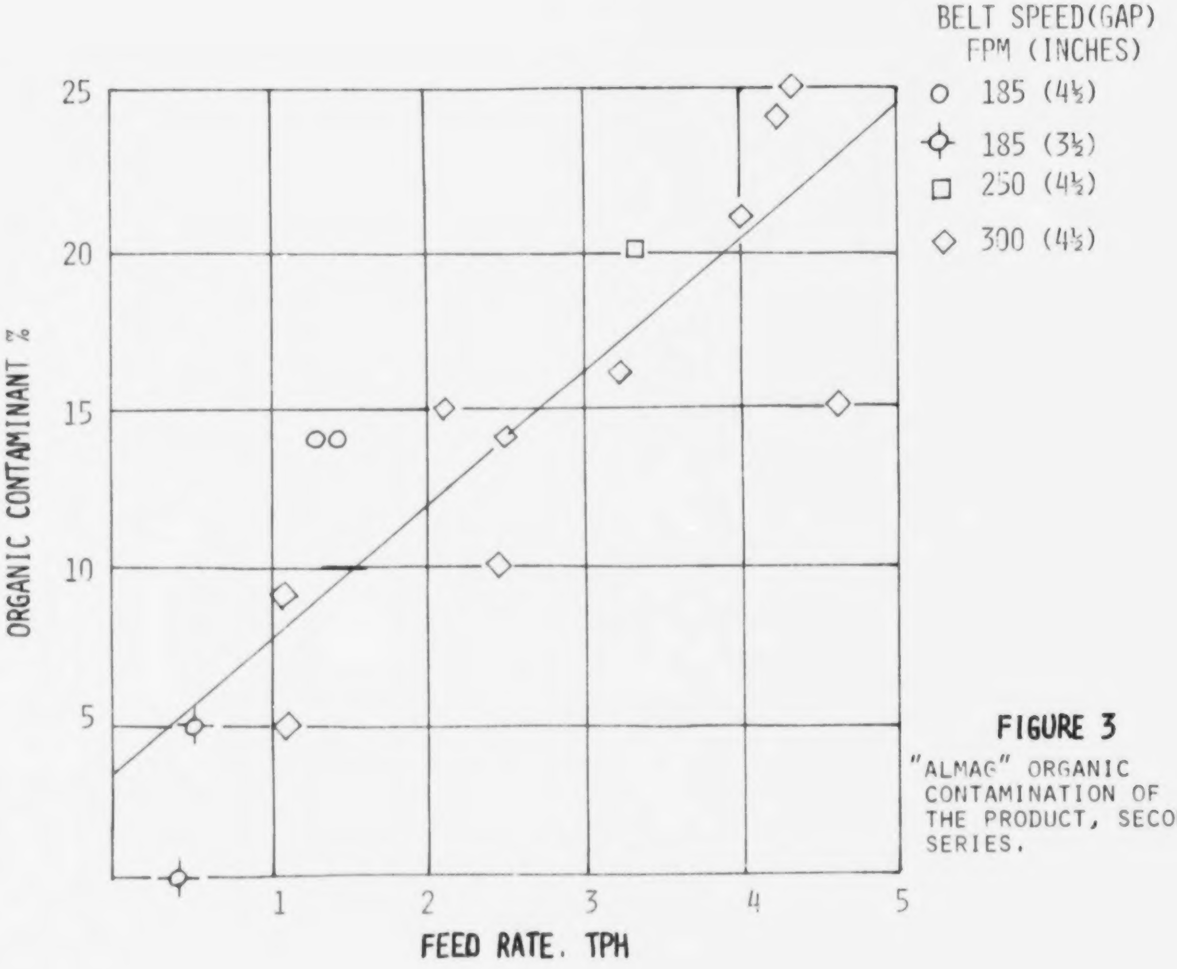
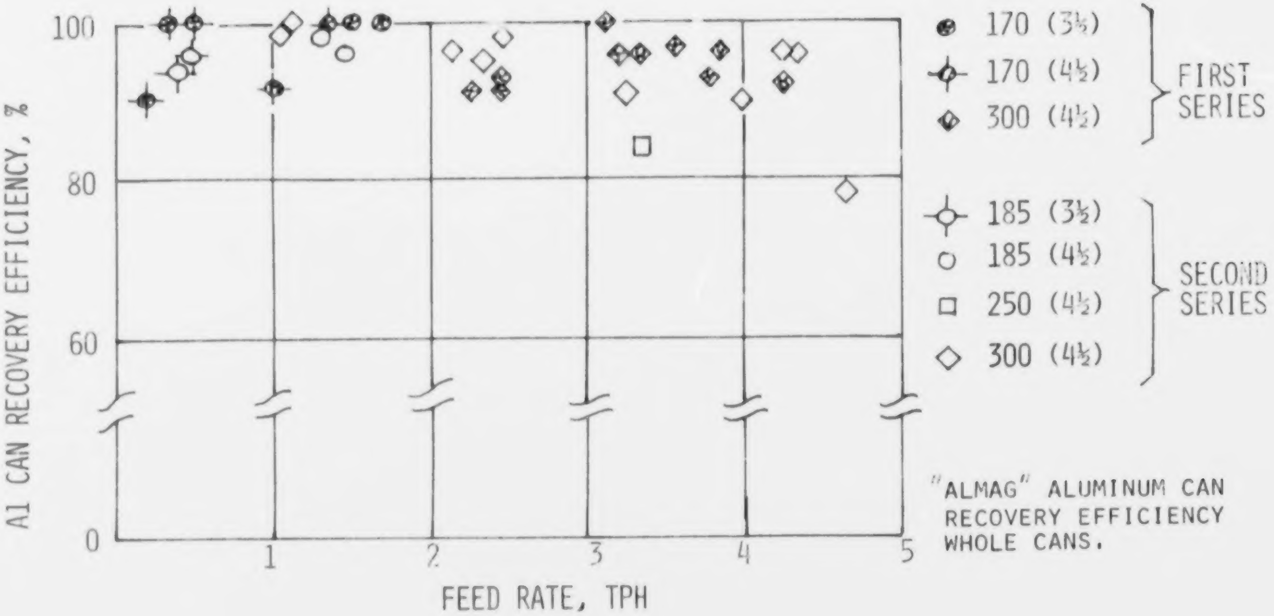


FIGURE 3

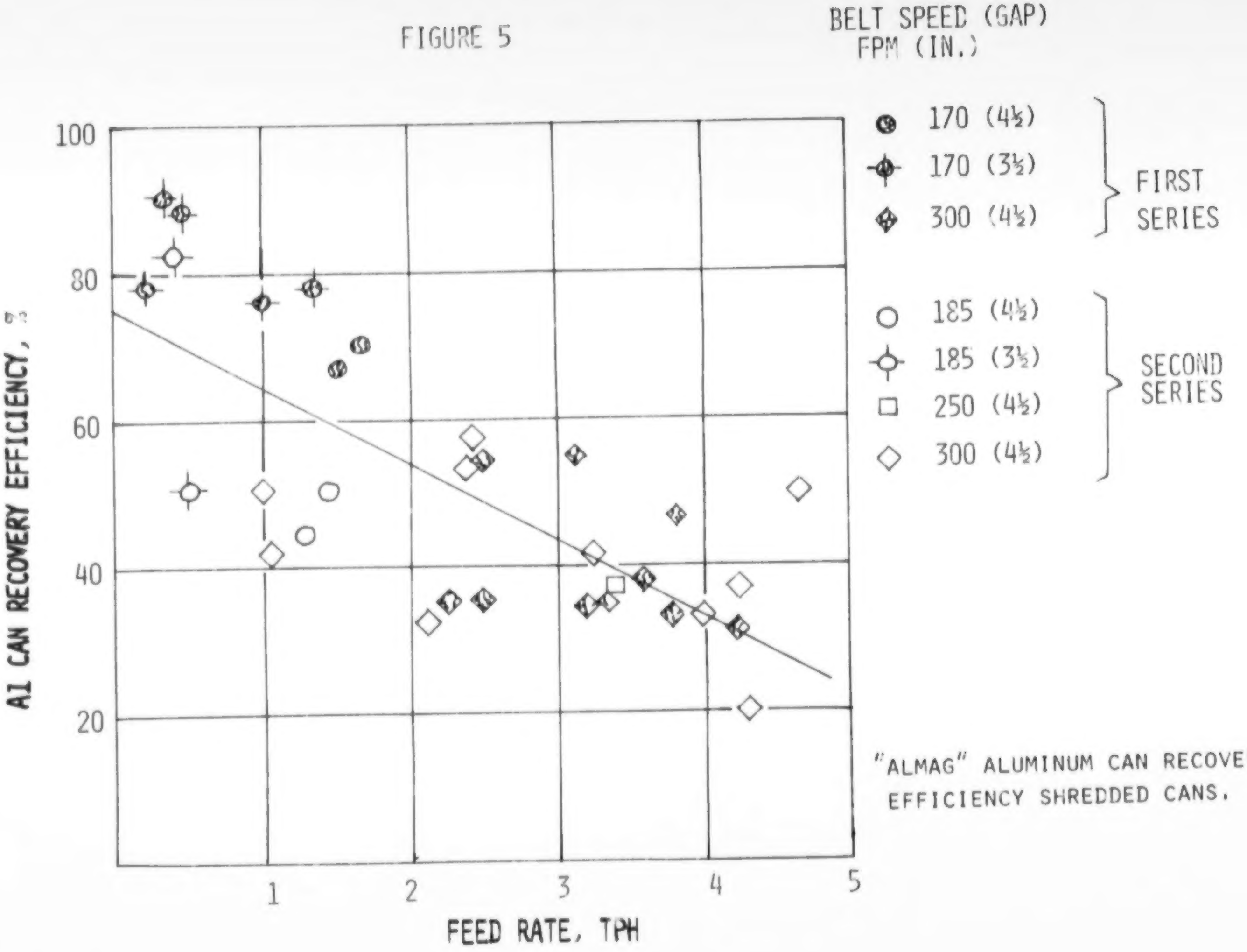
"ALMAG" ORGANIC CONTAMINATION OF THE PRODUCT, SECOND SERIES.

FIGURE 4



"ALMAG" ALUMINUM CAN
RECOVERY EFFICIENCY
WHOLE CANS.

FIGURE 5



"ALMAG" ALUMINUM CAN RECOVERY EFFICIENCY SHREDDED CANS.

FIGURE 6. GLASS RECOVERY PROCESS FLOW DIAGRAM

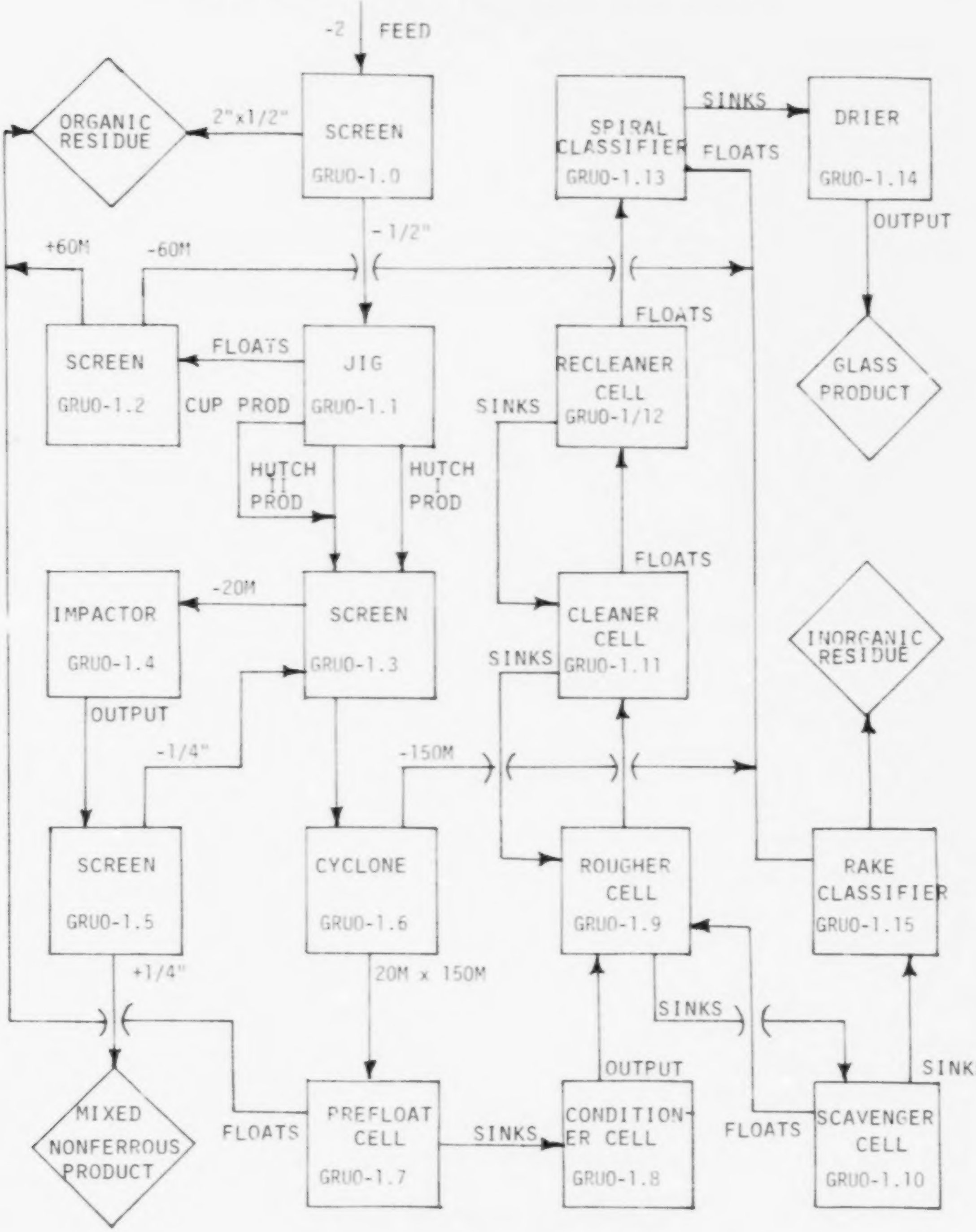

-2
FEED
SCREEN
GRUO-1.0
2"x1/2"
ORGANIC RESIDUE
-1/2"
+60M
-60M
SCREEN
GRUO-1.2
FLOATS
JIG
GRUO-1.1
CUP PROD
HUTCH II PROD
HUTCH I PROD
IMPACTOR
GRUO-1.4
-20M
SCREEN
GRUO-1.3
OUTPUT
-1/4"
SCREEN
GRUO-1.5
+1/4"
CYCLONE
GRUO-1.6
-150M
20M x 150M
MIXED NONFERROUS PRODUCT
FLOATS
PREFLOAT CELL
GRUO-1.7
SINKS
CONDITIONER CELL
GRUO-1.8
OUTPUT
ROUGHER CELL
GRUO-1.9
SINKS
SCAVENGER CELL
GRUO-1.10
FLOATS
SINKS
CLEANER CELL
GRUO-1.11
SINKS
FLOATS
RECLEANER CELL
GRUO-1/12
SINKS
FLOATS
SPIRAL CLASSIFIER
GRUO-1.13
SINKS
FLOATS
DRIER
GRUO-1.14
OUTPUT
GLASS PRODUCT
INORGANIC RESIDUE
RAKE CLASSIFIER
GRUO-1.15

Figure 7. Cross-Section of Bendelari Jig

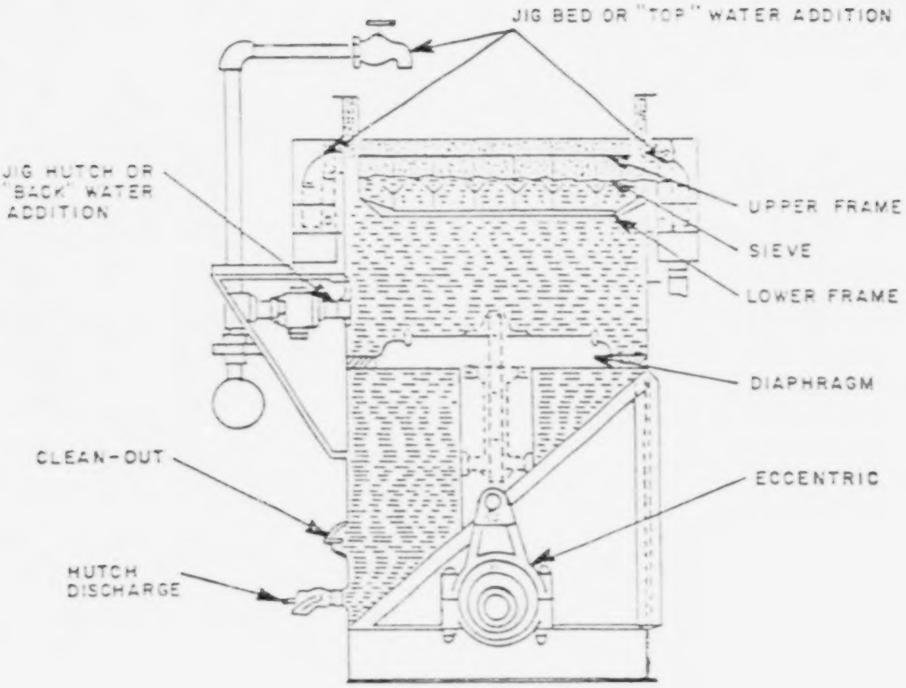

JIG BED OR "TOP" WATER ADDITION
JIG HUTCH OR "BACK" WATER ADDITION
UPPER FRAME
SIEVE
LOWER FRAME
DIAPHRAGM
CLEAN-OUT
ECCENTRIC
HUTCH DISCHARGE

Table 1

Description of ETEF Equipment

	ITEM	MANUFACTURER - MODEL	HP - DESCRIPTION	FUNCTION
1.	Primary Shredder	Williams Patent Crusher Co. Model 780	1000 hp horizontal hammermill, 24-230 lb. hammers, grates 9 x 12 in. 720 rpm (no load)	primary shredder
2.	Screen Feeder	Triple/S Dynamics Texas Shaker (with ball tray)	7 x 20 ft, 10 hp, ¼ in. punched plate on 7/16 in. staggered centers	screen shredded MSW to remove fines
3.	Air Classifier	- several, see ref. (6)	-	-
4.	Cyclone	Fisher-Klosterman Model XQ52 plus Carter-Day rotary valve Model AN-24 #1803	27' h, 8½' ℓ x 6' d barrel. De-entrainment box 5' x 4' x 8". Valve 2' d, 2 hp.	entrainment of light fraction
5.	Screen	Kennedy-Van Saun Model A	3/16 in. sq. openings 4' x 8', 1745 rpm, 31°	screen and feed light fraction
6.	Magnet No. 1	Eriez SP 630-SEL belt magnet	6'8" ℓ x 18" w belt 250 fpm, 1 hp, permanent magnet	recovery of magnetic metals
7.	Magnet No. 2	Permanent magnet	head pulley on 16" wide slider belt conveyor, 250 fpm	recovery of magnetic metals
8.	Trommel Screens	Combustion Power Co., part of Almag	3' d x 10' ℓ, 2" section and 4" section 1.5 hp, 27 rpm	screen feed to eddy current separator
9.	Eddy Current Separator	Combustion Power Co. Almag Model 20	25 kw @ 480 V. 2 gpm of cooling water	separation of aluminum
10-17	Glass Recovery Module	- see Table 4 -		

Table 4

Description of Glass Recovery Equipment

GLASS RECOVERY UNIT OPERATION (GRUO) NUMBER	DESCRIPTION OF UNIT OPERATION(S) PERFORMED	DESCRIPTION OF PIECE OF EQUIPMENT USED AND MOTOR SIZE
1.0	Screening at 1/2"	Link belt vibrating screen (2 hp) 2' x 8'
1.1	Jigging; sink-float separation; screening at 1/8"	42" x 42" duplex Bendelari jig (3 hp)
1.2	Screening at 60 M and dewatering	2' x 4' single deck vibrating screen (3 hp)
1.3/1.5	Screening at 1/4" (1.5) Screening at 20 M (1.3)	2' x 4' double deck vibrating screen (3 hp) 1/4" & 20 M screens
1.4	Size reduction	Impact hammermill (15 hp)
1.6	Size separation and dewatering	Cyclone 2-1/2" inlet, 3" overflow, 7/8" adjustable apex
1.7/1.8	Prefloat separation and conditioning of pulp for flotation	Flotation cells size, No. 12 (2)
1.9/1.10/ 1.11/1.12	Flotation	Flotation cells size No. 12 (4)
1.13	Classification & dewatering	24" x 13' spiral classifier (3 hp)
1.14	Drying	30" dia. x 20' horizontal direct fire dryer (3/4 hp)
1.15	Settling and classification	Settling tank & rake classifier (3/4 hp)

Table 5

Feed Characteristics - Composition of Streams, wt.% (Wet)

Material Stream	Glass, Rock, etc.	Wood	Metal	Plastic	Paper	<6.4 mm Fines*	Other**
<51 mm	24.3	4.1	3.2	4.1	16.9	33.7	13.7
51 x 13 mm	18.9	5.5	9.8	8.4	37.1	Trace	20.3
<13 mm	26.6	3.5	0.4	2.3	8.2	48.1	10.9

* Composition of <6.4 mm is predominately inorganic (glass, sand, ceramic)

** Includes food waste, leather, yard waste, textiles and unidentifiable

Table 6

ETEF Bendelari Jig Product Characteristics

CUP PRODUCT (avg. 4.1 kg)		HUTCH PRODUCT (avg. I = 17.1 kg, II = 6.4 kg)		ORGANIC RESIDUE (avg. 4.4 kg)		THROUGHPUT, Mg/h			
% H_2O	% Organic*	% H_2O	% Organic*	% H_2O	% Organic*	Cup Product	Hutch I Product	Hutch II Product	Residue
28.7	6.0	24.7	0.21	53.3	69.1	-	-	-	-
29.0	8.2	25.0	.30	59.2	80.3	-	-	-	-
20.4	3.7	23.5	.11	47.8	72.4	-	-	-	-
-	-	-	-	-	-	.15	.42	.18	.15
22.3	4.6	19.8	.07	52.5	83.6	.10	.58	.19	.16

---

* (1 - LOI) x 100

MID-SHAKEDOWN EVALUATION OF A DEMONSTRATION RESOURCE RECOVERY FACILITY

J. F. Bernheisel
National Center for Resource Recovery
1211 Connecticut Avenue, N. W.
Washington, D. C. 20036

ABSTRACT

The National Center for Resource Recovery developed a resource recovery demonstration facility in New Orleans, Louisiana. This facility processes 750 tons of refuse per day, and recovers metals and glass, and produces an unmarketed refuse-derived fuel (RDF). The test and evaluation program for this facility began in the latter part of 1977, prior to the plant's completion in March of 1978, with the development of test plans and procedures. Testing began during the shakedown period, and will continue for three years. To date, tests on the trommel show that screening prior to shredding produces a glass- and metals-rich fraction, and an organics-rich, low-ash fraction which can be further processed into a fuel. The tests conducted to date with the ferrous recovery system indicate that entrapped contaminants degrade the product quality. To satisfy the high quality requirements for this recovered product, modifications of the facility are being made.

INTRODUCTION

The resource recovery demonstration facility in New Orleans, Recovery 1, is currently in shakedown. NCRR participates in this project to demonstrate technical feasibility and to obtain performance information on recovery systems and equipment. Tests of the equipment in this demonstration facility are being conducted under contract with the U. S. Environmental Protection Agency, Municipal Environmental Research Laboratory. After a brief description of the process, the remainder of the paper describes the results obtained from the test work conducted to date. This will cover two efforts. First, the trommel, on which one test series in considerable depth has been conducted. Second, the ferrous metals recovery system, on which the first test in a comprehensive series and numerous quick samplings have been made. It is important to bear in mind that the data presented results from a testing and evaluation program in process. More refined data will be developed as the program continues.

PROCESS DESCRIPTIONS

The Recovery 1 simplified operational flow diagram is presented in Figure 1. Unit operations in the diagram are numbered. These numbers are repeated in Table 1, which gives the equipment description. Arrows indicate the paths that materials travel. Where appropriate, light and heavy components are identified. In Figure 1, it should be noted that the size of the individual figures have no relationship to the physical sizes of the machinery portrayed or the complexities of the equipment.[1]

Reduction Module. The raw, unprocessed refuse is brought into the Receiving Building by truck and deposited on the tipping floor. From this point, the refuse is pushed into one of the two conveyor pits by a front-end loader and is moved by the selected conveyor to the shredding equipment. There, 95 percent by weight of all large waste objects are reduced to less than four inches in size, and 99 percent are reduced to less than five inches in any direction. There is no absolute top size limit. The three major functions served by this processing are: (1) liberation of

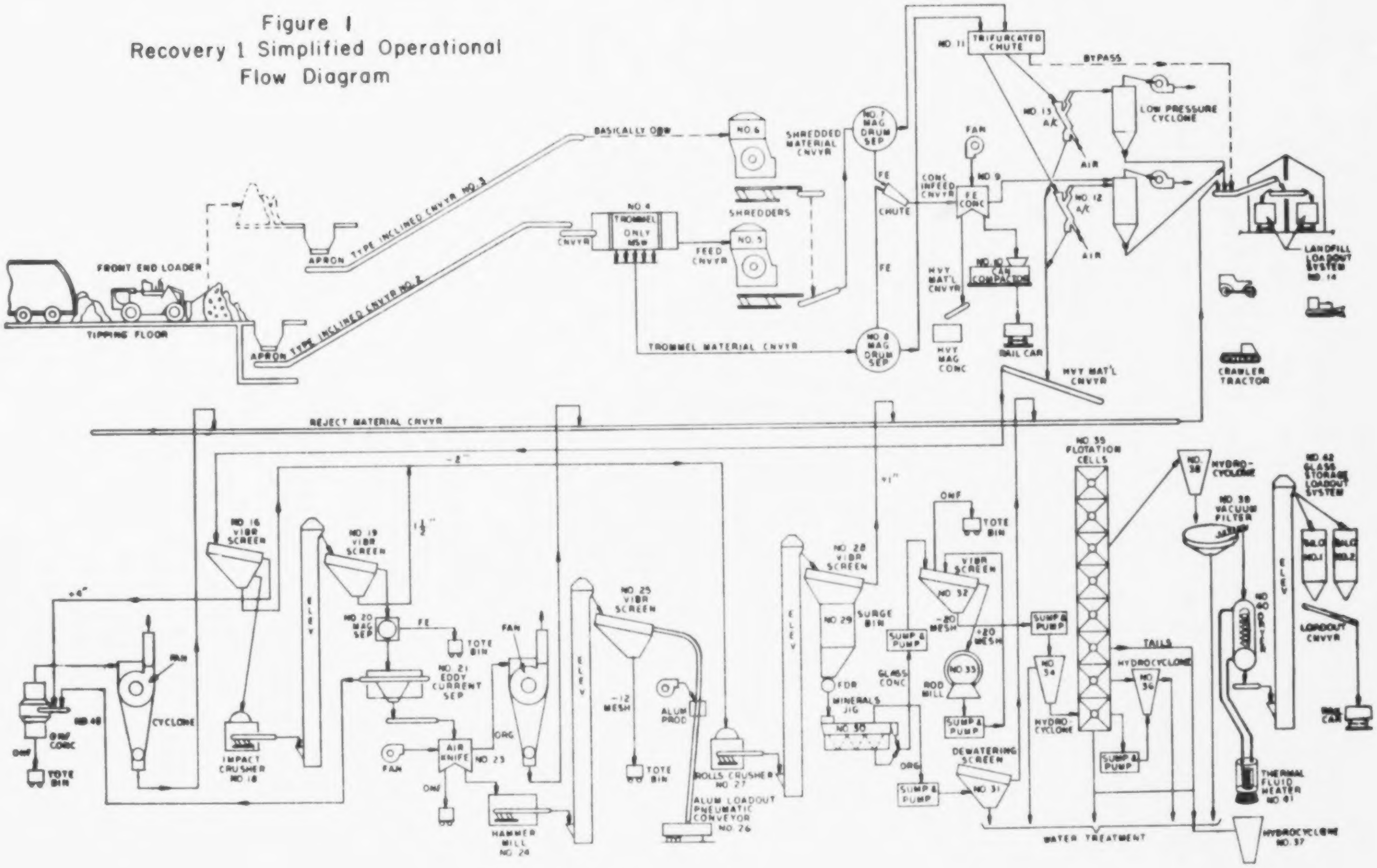

FRONT END LOADER
TIPPING FLOOR
APRON
APRON TYPE INCLINED CNVYR NO.3
APRON TYPE INCLINED CNVYR NO.2
BASICALLY OBW
CNVYR
NO.4 TROMMEL ONLY MSW
FEED CNVYR
TROMMEL MATERIAL CNVYR
NO.6
NO.5
SHREDDERS
SHREDDED MATERIAL CNVYR
NO.7 MAG DRUM SEP
NO.8 MAG DRUM SEP
FE
CHUTE
CONC INFEED CNVYR
FAN
NO 9
FE CONC
HVY MAT'L CNVYR
HVY MAG CONC
NO 10 CAN COMPACTOR
RAIL CAR
NO 11
TRIFURCATED CHUTE
BYPASS
NO 13 A/K
NO 12 A/K
AIR
LOW PRESSURE CYCLONE
LANDFILL LOADOUT SYSTEM NO 14
CRAWLER TRACTOR
HVY MAT'L CNVYR
REJECT MATERIAL CNVYR
-2"
+4"
CYCLONE
FAN
NO 48
ONF CONC
ONF
TOTE BIN
NO 16 VIBR SCREEN
IMPACT CRUSHER NO 18
ELEV
NO 19 VIBR SCREEN
1 1/2"
NO 20 MAG SEP
NO 21 EDDY CURRENT SEP
AIR KNIFE
NO 23
ORG
HAMMER MILL NO 24
NO 25 VIBR SCREEN
-12 MESH
ALUM PROD
ROLLS CRUSHER NO 27
ALUM LOADOUT PNEUMATIC CONVEYOR NO 26
+1"
NO 28 VIBR SCREEN
NO 29
SURGE BIN
FDR
MINERALS JIG
NO 30
GLASS CONC
SUMP & PUMP
VIBR SCREEN
NO 32
-20 MESH
+20 MESH
NO 33
ROD MILL
DEWATERING SCREEN
NO 31
NO 34
HYDRO-CYCLONE
NO 35 FLOTATION CELLS
TAILS
HYDROCYCLONE
NO 36
NO. 38
HYDRO-CYCLONE
NO 39 VACUUM FILTER
NO 40
THERMAL FLUID HEATER NO 41
HYDROCYCLONE NO 37
WATER TREATMENT
NO 42 GLASS STORAGE LOADOUT SYSTEM
SILO NO.1
SILO NO.2
LOADOUT CNVYR
RAIL CAR

Figure I
Recovery 1 Simplified Operational
Flow Diagram

TABLE 1. EQUIPMENT ITEM LIST

Equipment Number	Equipment Description
1	Truck scale
2	#1 line raw refuse feed conveyor system
3	#2 line raw refuse feed conveyor system
4	Trommel screen and discharge conveyors
5	#1 line shredder and discharge conveyors
6	#2 line shredder and discharge conveyors
7	Magnetic separator (drum type)
8	Magnetic separator (drum type)
9	Ferrous metals concentrator and cleanup
10	Ferrous metals--can compactor and loadout
11	Trifurcated chute
12	Air classifier #1
13	Air classifier #2
14	Landfill loadout system
15	Recovery building feed and discharge conveyors
16	4 x 2 vibrating screen
17	Heavy nonferrous metals concentrator
18	Impact crusher
19	Vibrating screen
20	Magnetic separator
21	Eddy current separator No. 1
22	Eddy current separator No. 2
23	Air knife
24	Aluminum hammermill

TABLE 1. EQUIPMENT TEST LIST (Cont'd)

Equipment Number	Equipment Description
25	12-mesh vibrating screen
26	Aluminum loadout
27	Rolls crusher
28	Vibrating screen
29	Surge bin
30	Minerals jig
31	Dewatering screen
32	Vibrating screen
33	Rod mill
34	Hydrocyclone No. 1
35	Flotation cell unit
36	Hydrocyclone No. 2
37	Hydrocyclone No. 3
38	Hydrocyclone No. 4
39	Vacuum filter
40	Glass product dryer
41	Thermal fluid heater
42	Glass storage and loadout system

composite materials; (2) size reduction to facilities recovery processing; and (3) a combination of size reduction and mixing to meet sanitary requirements of the landfill.

There are two independent shredding systems. The shredder of each is capable of processing at the average rate of 62.5 tons per hour (tph). Since there is a single discharge system, both shredders cannot operate simultaneously at full capacity.

Shredder Line No. 1 has a trommel screen (No. 4) preceding the shredder (No. 5). This is a rotating drum screen, approximately 45 feet long. Within the trommel, plastic and paper bags are broken open by lifters as the containers are tumbled. The smaller objects fall through the holes and are transported directly, without shredding, for recovery processing. The remaining material is conveyed from the trommel to the shredder (No. 5) for size reduction. The shredded material is then carried on a separate conveyor to magnetic separator (No. 7). Currently, this shredded material is sent directly to the landfill loadout area for transport to the landfill. This material is the potential refuse-derived fuel (RDF). The air classifier (No. 13) has not been installed, pending evaluation of its cost effectiveness.

Shredder Line No. 2 does not have a trommel. It is used as backup and for oversized waste. Its flow is shown as a broken line in Figure 1--the shredded output is moved to the air classifier area on the same conveyors as the shredded trommel oversized materials. Only a portion of this flow can be air classified by the air classifier (No. 12). However, the gates in the trifurcated chute can be adjusted to permit the second air classifier (No. 13) to receive the remainder of the flow when it is installed.

Ferrous Recovery System. Each discharge conveyor carries the material deposited on it, either as trommel underflow or shredded material, past a drum magnet. There are two discharge conveyors and, hence, two magnets (Nos. 7 and 8). The magnetic materials are deposited on a conveyor where they fall through a chute into a small air-classification device, the ferrous metals concentrator (No. 9). It has two functions: first, to blow off loose light materials which have been carried along with the ferrous materials at the magnetic separation step and, second, to separate the light ferrous metals, primarily can scrap, from heavier ferrous metals. This latter fraction is composed of shredded pieces of discarded bicycles, auto parts, trash cans, and other large items. The heavy ferrous fraction is discharged into a roll-off container for later transport to market. After densification by the compactor (No. 10), the light fraction is discharged into a railcar for later transport to market.

Air Classification. The initial equipment item in the air-classification area is a trifurcated chute (No. 11). This is a large, compartmented, steel-plated chute fitted with hydraulically actuated "flop gates." Its purpose is to: (1) distribute the waste stream flows between the two air classifiers; or (2) send part of the waste to the landfill if an air classifier malfunction occurs; or (3) bypass the air classifier entirely. As the flow diagram in Figure 1 indicates, the hopper is positioned between the magnetic drum separators and the air classifiers.

The principle of air classification is that the waste material is introduced into a rising column of turbulent air. Any object light enough to be buoyed upward by the rising air current is blown out the top and delivered to the landfill. Typically, this material is composed mostly of shredded bits of plastic, paper, and textiles. This would be the principal fuel fraction for energy recovery. Should it become economically feasible for the New Orleans facility to produce an energy product, this fraction could be used directly or be further processed. (This processing could include further size reduction, densification, or even conversion to gaseous or liquid fuel.) The air-classified shredded trommel overs appear to be an excellent candidate for low-ash fuel (RDF) because they have a high paper content and should be almost devoid of fines. As of now, the air-classified light fraction is to be landfilled, as described above.

Those objects which are heavy and fall in the air classifier, despite the upward air flow, are collected and conveyed into the Recovery Building. This heavy, primarily inorganic, fraction forms a glass, aluminum, and other nonferrous metals (ONF) concentrate. This material is transported into the Recovery Building for separation, cleaning, and preparation for shipment to the user industries. At this point, the ferrous metals have already been recovered, and the bulk of the waste (about 65 percent) has been sent to the landfill.

Within the Recovery Building, there are two product-oriented submodules. The first, the aluminum submodule, extracts the light-gauge aluminum, a small amount of ferrous metal, and the ONF. The second, the glass and ONF module, produces additional nonferrous metal, and its principal product, glass.

Aluminum Recovery System. The waste stream, which is made up of the heavy fraction from the air classifier, is deposited on a two-deck vibrating screen (No. 16). This screen separates the material into three sizes: larger than 4 inches, smaller than 2 inches, and between 4 and 2 inches (4 x 2-inch).

The plus 4-inch stream is routed to an air concentrator (No. 17) for the extraction of a small amount of nonferrous metals. The minus 2-inch, glass-rich stream is conveyed directly to the Glass Recovery System.

The 4 x 2-inch material stays in the Aluminum Recovery System. It is an aluminum-rich fraction of beverage cans, some aluminum of other types, and a small amount of other metals, including ferrous material, that escaped the large drum magnets. There are also glass, plastics, textiles, rubber, wood, etc. that escape. The entire 4 x 2-inch stream is processed by an impact crusher to break friable materials, such as glass and ceramics. Because aluminum is malleable, it is distorted, but not broken.

Particles smaller than 1-1/2 inches are separated on vibrating screen No. 19. This material, primarily glass, joins the minus 2-inch fraction separated earlier and is sent to the Glass Recovery System. Any waste larger than 1-1/2 inches continues in the flow, passing over a rotating drum magnet (No. 20) to remove residual ferrous metals. Removal of these metals is important to the proper operation of the eddy current aluminum separation device which follows.

The eddy current separator (No. 21) is a series of electromagnets set precisely above and below a belt conveyor. These produce a magnetic field through which the aluminum, other conductors, and nonconductors on the belt are conveyed. The movement of the conductors through the field creates an electric flow--an eddy current--within them. This, in turn, generates an associated magnetic field around the conductor. The polarities which occur cause the conductors to be repelled from the conveyor into a chute. This material drops into an air-knife classifier (No. 23) for further separation into three separate tractions: aluminum can stock, other metals, and organic carry-over.

Aluminum can stock is the primary output of this system. Because it is relatively low in density, it is passed through a small hammermill (No. 24) for size reduction of the individual cans and to increase the density of the product to 15-25 pounds per cubic foot. This reduces the product shipping costs. Fines are removed by screen No. 25. The shredded aluminum is moved by pneumatic conveyor No. 26 out of the building to a trailer truck for shipment to market. A small amount of mixed nonferrous fraction is also produced by the air knife.

Glass Recovery System. The small fractions (minus 2 and minus 1-1/2 inch material) obtained by screening in the aluminum system are conveyed to the glass recovery system. The glass is again crushed in the rolls crusher (No. 27). Screen No. 28 removes larger than 1-inch non-glass material. The undersized (smaller than 1 inch) fraction is processed by a minerals jig (No. 30). This piece of equipment, employed by the mining industry for many years, uses a vertically pulsed water flow to separate light and heavy materials. It produces a light organic fraction, a heavy glass-rich fraction, and a small amount of heavy nonferrous metals. After dewatering by screen No. 31, it is transported to the landfill.

The glass fraction is pumped as slurry to the second (or bottom) deck of a two-deck vibrating screen (No. 32). This second deck separates at 20 mesh, with larger particles going to a rod mill (No. 33) for crushing. The crushed material from the rod mill is pumped back to the screen. This time it enters on the first, or top, deck. Any material larger than 1/4 inch slides off the top deck and is saved. This material is predominantly nonferrous metal. The minus 20-mesh material (mostly glass, but containing some ceramics, stone, shell, and a very small amount of metal) is pumped as slurry to the glass cleanup area.

The first step in the glass cleanup is to remove the water used in previous steps and the very fine particles (less than 160 mesh). This process, called de-sliming, is accomplished by a hydrocyclone (No. 34).

The larger-sized solids are mixed with clean water in a prefloat tank to remove any remaining organic particles by floating them to the top of the tank and skimming them off.

The remainder of the glass cleanup is effected by froth flotation, a technique utilizing differences in the chemical properties of glass and the contaminants to achieve material separation. The glass and contaminants are mixed with a chemical reagent, which adsorbs preferentially to the surface of the glass. The coated glass attaches to bubbles formed by agitating the mixture with air. This glass-rich froth rises, is swept off the top, and is washed. Within the froth flotation cells (No. 35) downstream of the prefloat tank are: (1) a conditioner tank in which the chemical reagent is introduced to adsorb on the glass; and (2) a series of froth flotation cells where progressively more and more of the contaminants in the glass are removed.

The residue--the material or "tailings" not floated off--is pumped to the process water cleanup system. Here, suspended solids are settles out and discharged to landfill. Some of the water is recycled in the plant, while the remainder goes to a lagoon for reduction of biochemical oxygen demand (BOD) and chemical oxygen demand (COD) by oxidation.

The recovered glass is dewatered by a vacuum filter (No. 39) to a moisture content of less than 10 percent. The dewatered glass is then dried in a spiral dryer (No. 40) to less than one percent moisture. This device is an enclosed screw conveyor which has hot (650°F) heat exchange oil or thermal fluid circulating through the screw flites and the jacket surrounding the dryer trough. The heat conducted through the spiral and trough walls evaporates the moisture in the glass. After drying, the glass is stored in the glass storage and loadout system (No. 42).

TROMMEL TEST AND EVALUATION

The efficiency of a trommel to screen raw refuse was investigated in Great Britain in 1966.[2] Based on that experimental work, as well as wide experience in the minerals industry, a trommel was included in the process design for the recovery plant planned for the city of New Orleans in 1974.[3,4] At the same time, an experimental program was initiated by NCRR at its Equipment Test and Evaluation Facility (ETEF) in Washington, D. C., to provide supporting data for the design and specification of the trommel.[5] The experimental results indicated that the trommel could achieve separation of the minus 4-inch material with enrichment of the glass and metal portions of the MSW.[6] Most of the refuse bags were broken, thus liberating the contents. No serious blinding of the screen openings occurred, although textiles did hang on the wire cloth, they were constantly falling off and being replaced by other pieces.

One of the chief objectives of this pilot-scale experiment was to provide data and insight into sizing a production-scale trommel. Factors of interest were throughput capacity, speed of rotation, mass throughput per unit area or screening capacity, and angle of declination.

Description of Trommel. The trommel consists of four main components: a four-legged base structure, a dust shroud, the barrel, and the motors and drive system. The rotating barrel is 9.75 feet in inside diameter and 46.5 feet in overall length. It is constructed of 10 cylindrical sections, each 4.25 feet in length, with solid inlet and discharge lips attached to the first and last of the 10 sections. Each of the 10 sections contains seven removable screen plates, 4' x 4', constructed of 0.875" thick steel, curved to form the barrel. Each screen plate has fifty-six 4.75-inch diameter round holes located on 6-inch staggered centers, which corresponds to a 43.1 percent open screen plate area. Each plate has associated with it a lifter which is a blade-shaped steel projection intended to aid in the tumbling action and the opening of bags as well as to act as a screw to propel material forward.

The barrel is declined at five degrees and is rotated at nominally 11 rpm (45 percent of critical speed) by two 40-hp electric motors whose drive shafts may be interconnected to allow both shafts to be driven by one motor should the other motor fail.

Trommel Test Description. The principal objective of this first structured test of the trommel was to document its performance at nominal design conditions with comparison to experimental/design work where appropriate. The key measures of performance to be determined were: (1) mass split of the infeed between trommel underflow and overflow, (2) composition and size characteristics of the underflow and overflow, and (3) screening efficiency of the trommel by component. Additionally, some testing and analytical procedures were to be evaluated as to their practicability and validity.

Nominal design conditions are equivalent to operating the trommel in its "as-built" configuration at the rated capacity of 62.5 tph. The objectives were met by controlling the infeed mass rate to the trommel, allowing sufficient run time for start-up transients to be eliminated, then measuring the mass rates of the discharging trommel underflow and overflow to determine mass split of the infeed. Subsequent to the test run, a determination of composition of representative samples of the underflow and overflow and the fraction of each component misreporting (-4 inch) to the overflow was required to compute screening efficiency by component. Complementary analyses such as bulk density and moisture were also performed to further characterize the feedstock and output materials.

For Test Run 1, 25,640 pounds of raw refuse were used; for Test Run 2, 21,300 pounds were used. The measured throughputs were 62.4 tph and 58.2 tph, respectively. The throughput rate for each run was measured and verified by measuring the time necessary to process the known quantity of MSW.

Sampling of the raw refuse was done from the tipping floor. Sampling the product streams, shredded trommel overs and trommel unders, was done by running the respective conveyor systems for a total of 20 seconds and collecting the full flow of each. All samples were weighed immediately after collection.

Summary Results. Data were collected by sampling the two structured trommel test runs and measuring a number of parameters of interest. Table 2 shows the moisture for the trommel overflow, nominally plus 4-inch fraction, and underflow, nominally minus 4-inch fraction. The moisture in MSW is concentrated in the yard waste, paper, and food waste. The moisture in the trommel fractions is generally consistent with that observed for raw MSW in New Orleans. For example, the moisture of the raw MSW sample, taken in conjunction with Run 2, was 33.3 percent; the calculated trommel infeed for Run 2 was 31.6 percent.

The bulk density of the trommel fractions is also shown in Table 2. It will be noted that the bulk density of the underflow is considerably higher than the overflow. The factor of 4 to 5 lbs is to be expected from the difference in composition and size. Generally, the underflow contains small, dense material; the material in the overflow is larger and lighter.

Table 3 shows the percentage composition by component category of the trommel underflow and overflow for the two runs. These were determined by hand sorting samples and weighing each component for each run. Also shown is a calculated infeed composition for each run. These data were developed from the mass split and the composition of the individual fractions. The Run 1 overflow fraction for the "other heavy organics" category is approximately 41 percent of the sample. This is due to a large amount of textiles which comprised two-thirds of this component. Since the main objective of the sampling was to determine where materials reported and at what efficiency, no attempt was made to adjust the results for these statistical outliers.

The mass split between the two fractions is shown in Table 3. This split is approximately 55 percent to the underflow and 45 percent to the overflow, by wet weight. One function of the trommel at Recovery 1 is to concentrate metals and glass in the underflow for recovery. This has been successfully achieved for the glass, as shown in Table 3; however, it is not as marked in the aluminum and the ferrous metals, due to the presence of more large items.

The screening efficiency of the trommel by components is shown in Table 4. Screening efficiency was determined by analyzing the particle size of the overflow category. The material overflow which was smaller than four inches should have reported to the underflow. The amount of this misreporting material was added to the amount of the underflow material to obtain an estimate of the total amount of minus four-inch material for the category. This total was divided into the amount of the material reporting to the underflow in each category to determine screening efficiency.

In the case of aluminum and ferrous metals, a significant amount of material larger than four inches was contained in the raw MSW. A composite or overall efficiency can be calculated as 85 percent for Run 1 and 78 percent for Run 2. Generally, the component efficiencies are quite good, with the exception of the "other heavy organics" category in Run 1. This run included the textiles, which affected the efficiency.

In addition to the data presented here for the trommel fractions, one other set of measurements was made. This concerned the fuel properties of the trommel overflow after shredding. Samples 1 and 2 were taken during test Runs 1 and 2, respectively. These were separate samples of material from those analyzed for composition. Sample 3

TABLE 2. MOISTURE AND BULK DENSITY MEASUREMENTS

	Run 1	Run 2
Trommel Underflow		
Moisture	24.1%	26.5%
Bulk Density		
Minimum	20.5 lb/ft^3	16.4 lb/ft^3
Maximum	25.7	21.9
Average	22.6	19.4
Number of measurements	6	4
Trommel Overflow		
Moisture	21.0%	36.9%
Bulk Density		
Minimum	4.40 lb/ft^3	4.69 lb/ft^3
Maximum	5.20	6.60
Average	4.72	5.46
Number of measurements	4	7

TABLE 3. TROMMEL FRACTION COMPOSITION

(Wet Weight or "As Received" Basis)

	Underflow (%)		Overflow (%)		Calculated Infeed (%)	
Component	Run 1	Run 2	Run 1	Run 2	Run 1	Run 2
Mass split	58.2	54.7	41.8	45.3		
Paper products	12.0	28.5	47.6	69.4	26.9	47.0
Yard waste	14.9	6.9	2.6	7.1	9.8	7.0
Plastics	2.1	2.6	4.5	5.2	3.1	3.7
Other heavy organics	10.7	11.3	40.8	9.9	23.2	10.7
Ferrous metals	3.7	7.3	3.2	6.6	3.5	7.0
Alumunim	0.5	1.1	0.1	1.1	0.3	1.1
Other nonferrous	0.1	0.2	0.0	0.0	<0.1	0.1
Glass	24.2	28.3	0.4	0.3	14.3	15.6
Stones & ceramics	5.7	2.3	0.0	0.0	3.3	1.2
Minus 1/4" fines	26.2	11.6	0.9	0.4	15.6	6.5

TABLE 4. TROMMEL SCREENING EFFICIENCY BY COMPONENT

(% Wet Weight or "As Received" Basis)

Component	Run 1	Run 2
Paper	73.6	61.8
Yard waste	92.3	64.1
Plastics	78.2	70.5
Other heavy organics (food, rubber, leather, textiles, and wood)	51.9	80.8
Ferrous metals	84.8	79.8
Aluminum	92.3	89.8
Other nonferrous metals	100.0	100.0
Glass	98.8	99.1
Stones and ceramics	100.0	100.0
Minus 1/4" fines	97.6	97.5

was taken prior to the other two and was not part of the structured test, and Sample 4 was taken after the structured test. Additional samples are being taken and analyzed as part of the on-going program. Table 5 shows the heating value, moisture, ash, and sulfur results for these samples.

From the data developed by the testing at Recovery 1 and presented here, it can be concluded that the trommel achieves two of its design goals. It concentrates metals and glass for materials recovery, and it produces a quality refuse-derived fuel fraction. While there is a loss of potential fuel to the trommel underflow, it would appear that this would be acceptable in the many situations where a low ash content is of primary concern. Processing of the unders fraction could produce additional material to be used as fuel. Additional data from these tests can be found in Reference 7.

FERROUS METALS RECOVERY

Ferrous metals recovery from MSW has been practiced for a long time. It has been reported that as of July 1978 facilities in 36 cities were recovering ferrous metals.[8] A first look would indicate that ferrous metals recovery was a simple task, given the magnetic quality of most ferrous metals. A magnetic separator suspended over an open stream of MSW should suffice. However, in practice, ferrous recovery is more difficult than it first appears.

The difficulty in ferrous recovery is the contaminants which are brought along with the ferrous metal during magnetic separation. Some contaminants are inherent in the construction of the ferrous items in MSW. For example, "tin cans," which constitute 85 percent or so of the ferrous metal in MSW, are sheet steel, covered by a tin plating with a soldered seam. Also, some have aluminum tops, and all have organic lacquer interior coatings. In addition, some form of label, either paper or painted, is usually used. However, the contaminants which cause the most problems come from other sources. These are: (1) loose nonferrous materials from the MSW which are carried along with the ferrous metals during magnetic separation, and (2) nonferrous materials entrapped in the

TABLE 5. RDF CHARACTERISTICS

(Shredded Trommel Overflow)

	Sample No. 1	Sample No. 2	Sample No. 3	Sample No. 4	Average
Btu/lb*	7624	5563	8174	7551	7228
Moisture $	19.0	32.5	--	20.6	24.0
Ash* %	10.2	5.5	13.6	13.6	10.7
Sulfur* %	<0.1	<0.1	<0.1	0.3	--

---

*Dry weight basis.

ferrous metal. This latter category is usually residual material left in containers after use or materials put in the containers for disposal. All of these contaminants are primarily organic.

The presence of these contaminants changes the function of the magnet from recovering ferrous metals to producing a magnetic concentrate. This concentrate, while predominantly ferrous metals, contains sufficient nonferrous material to require further processing. The extent of the processing depends upon the original contaminant level, the processing prior to magnetic separation, and the requirements of the user who is buying the ferrous product. Many approaches have been taken to beneficiate the magnetic concentrate. The processing steps used in these approaches include shredding, air classification, screening, and additional magnetic separation. The approach taken at Recovery 1 and its effectiveness is discussed below.

An example of a user specification is shown in Table 6. Notice that the specification refers only to steel cans. Can lids, bottle tops, and other light sheet steel are generally acceptable in small concentrations. However, the presence of larger iron castings or steel forging may not be. Specifications like this one will require a separation of ferrous metal recovered from MSW into a light ferrous fraction, which is mainly can stock, and a heavy fraction for most markets. The heavy fraction, which can be marketed separately if clean enough, comprises from 10 to 20 percent of the recovered ferrous product.[9,10]

Description of Ferrous System. As discussed earlier and shown in Figure 1, there are two independent magnetic separators. These operate on the two material streams from the reduction module: (1) trommel underflow and (2) shredded trommel overflow.

The trommel unders magnet (No. 8) is a 42-inch diameter drum, 54 inches wide. The shredded trommel overs magnet (No. 7) is a 48-inch diameter drum, 72 inches wide. Each of these units is mounted above the head pulley of its respective feed conveyor. The arrangement of the magnets and conveyors is shown in Figure 2. The trommel unders magnet is at 15 inches and 26.3 degrees from its conveyor; the shredded trommel overs magnet is at 22.5 inches and 24.2 degrees from its conveyor. (The distance is measured from the drum surface to the conveyor surface on the line joining the center of the drum and the conveyor head pulley. The angle is measured between this line and the vertical.) The rotation of the drums carries the attached material up and over to a single discharge belt. The combined magnetic material stream, ferrous metals plus contaminants, is fed to a two-stage air cleanup device called the ferrous concentrator (No. 9). This unit uses an upward flow of turbulent air and vibration to remove the loose organic material. Subsequently, a high-velocity horizontal air stream separates lighter sheet steel from heavier castings, forgings, etc. The heavy ferrous metal is carried by conveyor to a tote bin. The light ferrous metal is delivered to the compactor (No. 10) by a second conveyor. A quality control observer

FIGURE 2. MAGNETIC DRUM PLACEMENT

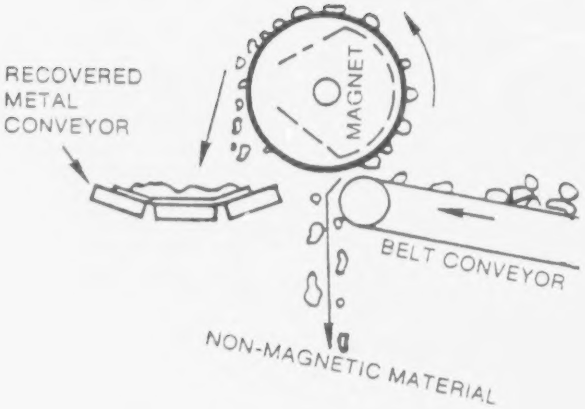

RECOVERED
METAL
CONVEYOR
MAGNET
BELT CONVEYOR
NON-MAGNETIC MATERIAL

TABLE 6. ORIGIN SPECIFICATION FOR STEEL-CAN BUNDLES

Tin-coated or uncoated scrap steel cans, compressed before or after shredding to a density of not less than 75 pounds per cubic foot. Maximum bundle size is 24" x 24" x 60". Steel beverage cans, with or without aluminum tops, may be included. Must be free of incinerated cans, all-aluminum cans, copper and other nonferrous metals (except those used in steel can construction). Aluminum content of bundles must be less than 4 percent. Dirt, plastics, and loose organics (food wastes, paper, etc.) must be less than 5 percent.

Source: United States Steel Corporation, July 15, 1976.

removes any remaining large contaminants at this point. The compactor is a 36-inch diameter hydraulic ram which compresses the light ferrous into a 12-inch thick disc with a 25 pound per cubic foot diameter. These fall by gravity into a railcar below.

Ferrous Test Description. A number of samplings of the raw MSW on the tipping floor have been analyzed for ferrous content. This was done by randomly selecting a 500- to 1,000-pound sample with the front-end loader. This is weighed and moved to an analysis area for immediate analysis. Samples have been taken of the feed material to both magnets by stopping these conveyors and removing the entire burden for a specified length. This can be related to material flow by knowing the belt speed. Samples of the products of the two magnetic separators have also been taken. This is done by turning off both magnets and their discharge conveyor. The magnet to be tested is then activated under controlled conditions and a timed sample is collected on the discharge conveyor. This sample is removed, weighed, and bagged for later analysis. Finally, samples have been taken of the light ferrous product. These are taken by locking the door of the compactor (No. 10) open so no compaction takes place. The uncompacted material is collected in a container for a predetermined period. No samplings of the ferrous concentrator (No. 9) streams have been formally conducted. These are planned for 1979.

The samples taken as described above are analyzed. The ferrous metals with their entrapped nonferrous materials are manually removed from any loose contaminants. The ferrous metals are categorized as light and heavy and each of the three categories weighed (light, heavy, and loose nonferrous material). The light ferrous and the heavy ferrous fractons are each manually cleaned. This involves freeing entrapped material. In the case of cans, the paper labels are removed and any contents are scraped out. Samples were initially washed and oven dried, but this step was eliminated when it was found that only one percent additional contaminant was removed in this manner. The American Society for Testing and Materials has under consideration a test procedure using an oven at about 500°F to remove organic contaminants. A comparison of the two methods will be made.

Summary Results. The composite of all three ferrous recovery system samplings is represented by the flow in Figure 3. This shows the clean light ferrous metal as comprising 4.8 percent of the incoming MSW. An additional 0.6 percent of the waste is heavy ferrous metal. As can be seen, there is an entrapped contaminant level of 37 percent in the light ferrous, and 43 percent in the heavy.

As indicated in Table 7, the feedstocks for the two magnetic separators (Nos. 7 and 8) are very similar in general composition. However, a review of Tables 2 and 3 will indicate two major differences. First, the loose contaminants in the trommel unders contain 40 to 50 percent glass, stones, and grit. This contributes to the second, which is a bulk density difference of a factor of four to five. The shredded trommel overs have roughly the same density as the unshredded. The composition of the product streams shows that both magnets produce ferrous metals concentrates. However, the total concentration of ferrous metals is lower in the shredded trommel overs magnet product, and the concentration of light ferrous is lower still. This indicates that the shredded trommel overs magnet is not

FIGURE 3. ESTIMATED FERROUS FLOW

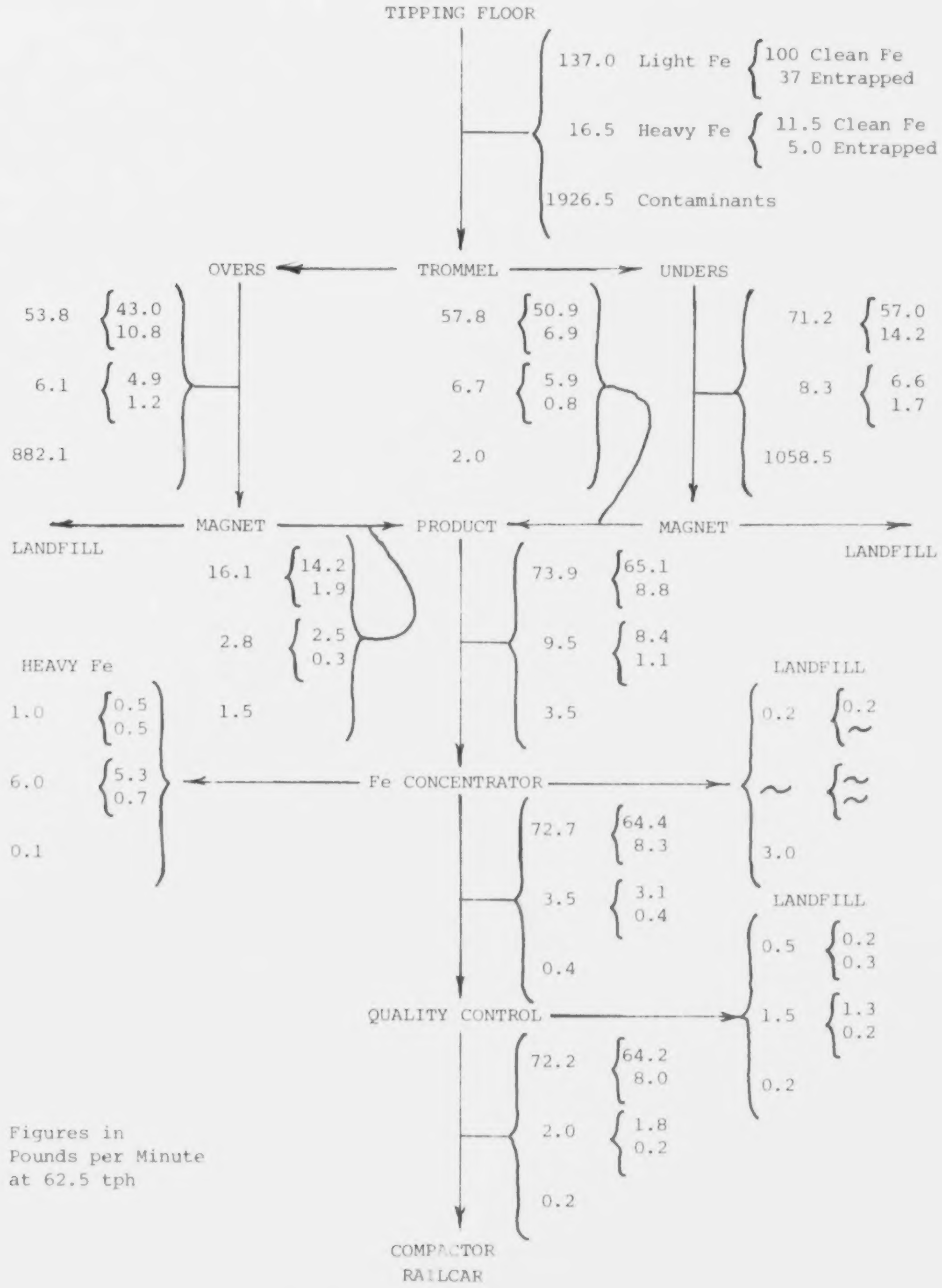

TIPPING FLOOR
137.0 Light Fe
100 Clean Fe
37 Entrapped
16.5 Heavy Fe
11.5 Clean Fe
5.0 Entrapped
1926.5 Contaminants
OVERS
TROMMEL
UNDERS
53.8
43.0
10.8
6.1
4.9
1.2
882.1
57.8
50.9
6.9
6.7
5.9
0.8
2.0
71.2
57.0
14.2
8.3
6.6
1.7
1058.5
LANDFILL
MAGNET
PRODUCT
MAGNET
LANDFILL
16.1
14.2
1.9
2.8
2.5
0.3
1.5
73.9
65.1
8.8
9.5
8.4
1.1
3.5
HEAVY Fe
1.0
0.5
0.5
6.0
5.3
0.7
0.1
Fe CONCENTRATOR
LANDFILL
0.2
0.2
~
~
~
~
3.0
72.7
64.4
8.3
3.5
3.1
0.4
0.4
LANDFILL
0.5
0.2
0.3
1.5
1.3
0.2
0.2
QUALITY CONTROL
72.2
64.2
8.0
2.0
1.8
0.2
0.2
Figures in
Pounds per Minute
at 62.5 tph
COMPACTOR
RAILCAR

TABLE 7. MAGNETIC SEPARATOR PERFORMANCE

Component	Trommel Unders Magnet		Shredded Trommel Overs Magnet	
	Feed	Product	Feed	Product
Light magnetic fraction	6.3	86.9	5.7	78.9
Light ferrous	5.0	76.5	4.6	69.6
Entrapped nonferrous	1.3	10.4	1.1	9.3
Heavy magnetic fraction	0.7	10.1	0.6	18.7
Heavy ferrous	0.6	8.9	0.5	12.3
Entrapped nonferrous	0.1	1.2	0.1	1.4
Loose contaminants	93.0	3.0	93.7	7.4

performing as well as the trommel unders magnet. This conclusion is supported by the comparison of separation efficiencies shown in Table 8. Efficiency is defined as the percentage of the component of interest in the feed which is delivered to the preferred product stream.

The efficiency of the trommel unders magnet for both light and heavy ferrous metals is 89 percent. The efficiency for the two magnetic fractions is lower, at 81 percent. This indicates that the magnet is less efficient on those items which entrap heavy non-magnetic materials, as would be expected. Also, this may be a desired result; it keeps some entrapped contaminants from overloading the cleanup system. The comparison between the two magnets reveals a marked difference in efficiency. This is due to non-optimum placement of the shredded trommel overs magnet. The problem has been physical interference between the magnet and the low bulk density shredded material. A stronger magnet may be required.

The efficiency of the ferrous concentrator is shown in Table 9. It is lower than desirable in two critical areas. First, the separation of the light ferrous product from the heavy ferrous product is not good enough. The problem, as shown in the table, is that some 36 percent of the heavy magnetic fraction remains with the light ferrous product. While this amounts to only five percent of the light ferrous product by weight, it is a highly visible contaminant. This is due to the entrapped nonferrous material contained in this material. As can be seen in the table, the majority of the material removed by the quality control observer is in this category.

The final light ferrous metal product composition is shown in Table 10. This shows the product to be 86 percent light ferrous metal, with the caveat that the contaminants discussed earlier which are used in can manufacture are not counted. The other contaminants constitute 11 percent of the product. The specification given in Table 6 calls for these contaminants to be less than five percent. The light ferrous product from Recovery 1 does not meet this specification. It is not as clean as we would like to deliver to our customer, Proler International. It will not meet the ASTM specifications under consideration.

Processing of trommel unders and shredded trommel overs at Recovery 1 leads to a light ferrous metal product which is not marketable under the specifications being adopted by users. Neither component of the fraction removed by the magnets from the shredded trommel unders or those removed from the shredded trommel overs will meet the specifications. The conclusion NCRR has reached is that additional processing is required. Further, additional stages of magnetic scalping or air classifying will not suffice. Some working of the metal is required to open enclosures and free entrapped material. The use of a shredder for this purpose is being analyzed and tested. This shredding operation should be followed by a cleanup stage, either air

TABLE 8. COMPARISON OF MAGNET EFFICIENCY

Component	Trommel Unders	Shredded Trommel Overs
Light magnetic fraction	81.2	29.9
Light ferrous	89.3	83.0
Entrapped nonferrous	48.6	17.6
Heavy magnetic fraction	80.7	45.9
Heavy ferrous	89.4	51.0
Entrapped nonferrous	47.1	25.0
Loose contaminants	0.2	0.2

TABLE 9. FERROUS CONCENTRATOR EFFICIENCY

	Efficiency	
Component	Light Product	Heavy Product
Light magnetic fraction	98.4	1.4
Light ferrous	98.9	0.8
Entrapped nonferrous	94.3	5.7
Heavy magnetic fraction	36.8	63.2
Heavy ferrous	36.9	63.1
Entrapped nonferrous	36.4	63.6
Loose contaminants	11.4	2.9

TABLE 10. LIGHT FERROUS METAL PRODUCT

Component	Composition in Percent
Light magnetic fraction	97.0
Light ferrous	86.3
Entrapped nonferrous	10.7
Heavy magnetic fraction	2.7
Heavy ferrous	2.4
Entrapped nonferrous	0.3
Loose contaminants	0.3

classification or magnetic separation. The latter is preferred, and both would be better. Such a system is being designed for implementation at Recovery 1.

ACKNOWLEDGEMENT

This paper is based upon tests conducted by Perry Bagalman and Kelly Runyon of NCRR's New Orleans staff.

This testing project is supported in part by the U. S. Environmental Protection Agency (Contract No. 68-01-4423) under the direction of Mr. Donald Oberacker, Project Officer for the Municipal Environmental Research Laboratory in Cincinnati, Ohio. The cooperation of the City of New Orleans, the project sponsor, and Waste Management, the project operator, are gratefully acknowledged. No endorsement of this paper by any of the above is implied.

REFERENCES

1. National Center for Resource Recovery, Inc., New Orleans Resource Recovery Facility Implementation Study - Equipment, Economics, Environment, Washington, D. C.: National Center for Resource Recovery, Inc., 1977, 427 pp.

2. Warren, J. L., "The Use of a Rotating Screen as a Means of Grading Crude Refuse for Pulverization and Compression," Resource Recovery and Conservation, Vol. 3, No. 1, March 1978, pp. 97-111.

3. Taggart, A. F., Handbook of Mineral Dressing, New York: John Wiley & Sons, Inc., 1945, pp. 7-27 - 7-34.

4. National Center for Resource Recovery, Inc., Resource Recovery and Disposal Program - Bid Specifications for Facilities and Operation, prepared for the City of New Orleans, LA, Washington, D. C.: National Center for Resource Recovery, Inc., 1974, 602 pp.

5. National Center for Resource Recovery, Inc., Materials Recovery System, Engineering Feasibility Study, Washington, D. C.: National Center for Resource Recovery, Inc., 1972, 365 pp., Supplement, 1974, 108 pp.

6. Woodruff, K. L., "Preprocessing of Municipal Solid Waste for Resource Recovery with a Trommel," Transactions of SME, AIME, Vol. 260, September 1976, pp. 201-204.

7. Trommel Initial Operating Report, Recovery 1, TR 78-3; Washington, D. C.: National Center for Resource Recovery, Inc., 1978, 26 pp.

8. Kinsey, R. D., and Hildebrand, B. D., "Solid Waste Processing Facilities," Washington, D. C.: American Iron and Steel Institute, 1978, 724 pp.

9. Sullivan, P. M., and Makar, H. V., "Quality of Products from Bureau of Mines Resource Recovery Systems and Suitability for Recycling," Proceedings of the Fifth Mineral Waste Utilization Symposium, Chicago, IL: U. S. Bureau of Mines and IIT Research Institute, April 13-14, 1976, pp. 223-233.

10. Systems Technology Corporation, "A Technical, Environmental and Economic Evaluation of the Wet-Processing System for the Recovery and Disposal of Municipal Solid Waste," report prepared for the U. S. EPA, Office of Solid Waste Management Programs, Contract No. 68-01-2211, Washington, D. C.: U. S. Environmental Protection Agency, 1975, p. 87.

RESEARCH AND EVALUATION OF SOLID WASTE PROCESSING EQUIPMENT

David Bendersky and Bruce Simister
Midwest Research Institute
425 Volker Boulevard
Kansas City, Missouri 64110

ABSTRACT

This paper summarizes the results of a multiphase study of processing equipment used in solid waste resource recovery plants, conducted during the period 1976 to 1978. In the first phase, the research needs were established. The subsequent phases were devoted to in-plant tests and evaluations of nine shredders, two magnetic separators, one air classifier, and tests of ambient air emissions at two resource recovery plants.

The initial investigation revealed the need for considerable research on solid waste processing equipment. Forty specific research needs were identified and categorized into 13 areas: general, shredders, magnetic separators, air classifiers, screens, dryers, densifiers, conveyors, storage and retrieval, receiving facilities, controls, fires and explosions, and economic research needs. Tests of the magnetic separators show that both systems recovered about 80 percent of the available ferrous metal, but there were considerable differences in the amount of energy consumed and the purity of the recovered metal. The air classifier tests indicate that there is a critical air to solids ratio for optimum performance. The air emissions tests show that the processing of solid wastes does not produce harmful particulates, heavy metals, or asbestos levels. The tests of shredders were conducted by and are presented in a separate paper by Cal Recovery Systems.

INTRODUCTION

The need for better waste disposal techniques combined with the need for new energy sources has stimulated considerable interest and activity in the development of processing plants to convert municipal solid wastes into energy products and to recover other resources in these wastes. These plants process the raw waste through various combinations of equipment which include one or more of the following operations: shredding, magnetic separation, air classification, screening, drying and densification. In addition, there is materials handling and other auxiliary equipment associated with the operations such as receiving facilities, conveyors, dust collectors, storage and retrieval bins, and electrical controls.

Municipal solid waste (MSW) is a difficult material to handle and process. Some of the characteristics of MSW that contribute to the difficulty are: it is a mixture of many different materials, shapes and sizes; it does not flow well; it contains abrasives; the moisture content varies considerably; it is putrescible, and it tends to compact in storage. Furthermore, much of the equipment being used to process MSW was not originally designed for this purpose. Thus far, operating experience, tests and evaluations of waste processing plants have been insufficient to provide a firm basis for optimum design, selection and operation of equipment for these plants.

In light of this situation, the U.S. Environmental Protection Agency contracted the Midwest Research Institute to conduct a study of processing equipment for the recovery of energy and other resources from municipal solid wastes. The study, initiated in 1976, was divided into three phases. The first phase was devoted to a study of the state of the art of waste processing systems and equipment to delineate the research needs.(1) The second phase of the study was devoted to in-plant tests of two magnetic separators, an air classifier, and air emissions.(1) The third phase involved in-plant tests of 8 shredders.(2)

RESEARCH NEEDS

The sources of information used to establish the research needs for solid waste processing equipment included a literature review of over 200 relevant documents, a survey of 54 existing and planned resource recovery systems and associated processing equipment; visits to seven resource recovery plants; and personal discussions with representatives of organizations that have designed resource recovery systems, manufacturers of waste processing equipment, and operators of resource recovery plants.

The investigation revealed the need for considerable research (and development) on processing equipment for resource recovery systems. There is a lack of important information which is needed by systems designers, equipment manufacturers and processing plant operators. Systems designers need more performance data about available processing equipment so that they make choices based on firm data. Equipment manufacturers need to know more about the conditions under which their equipment must operate. And, plant operators need more information concerning the optimal conditions for operating and maintaining individual pieces of equipment and systems, based on firm cost-effectiveness data.

Forty specific research needs for resource recovery processing equipment were identified, and are listed below. Some of these research needs have recently been at least partially satisfied, which are asterixed, but many still remain.

General

1. Determine the optimal arrangement(s) of solid waste processing equipment.
*2. Study emissions from solid waste processing equipment.
3. Determine solid waste characteristics pertinent to equipment performance.
4. Evaluate new types of waste processing equipment.

Shredders

*5. Compare the performance of various types of shredders.
6. Determine optimum maintenance procedures and schedules.
7. Determine most effective hammer profiles and arrangements.
*8. Establish shred size requirements for various fuel applications.
*9. Evaluate the effectiveness of single vs multiple shredders.

Magnetic Separators

*10. Determine the optimal operating conditions for magnetic separators.
11. Compare the performances of belt and drum magnets.

Air Classifiers

*12. Determine the optimal conditions for air classifiers.
13. Compare the performance of the various types of air classifiers.

Screens

*14. Determine the effectiveness of prescreening solid wastes.
15. Compare the performance of various types of screens.

Dryers

16. Determine the effects of drying on separation.
17. Determine the effects of drying on the storability of RDF (refuse derived fuel).
18. Evaluate the effect of drying on the combustion characteristics of RDF.
19. Evaluate the effects of drying on bacteria and virus in RDF.

Densifiers

20. Establish the specification for densified RDF.
*21. Determine the optimal operating conditions for densifiers.

Conveyors

22. Determine the performance of various types of conveyors for waste processing.
23. Determine the optimal operating conditions for conveyors.

Storage and Retrieval

24. Compare the performance of various storage and retrieval systems for RDF.
25. Determine the optimal operating conditions for storage and retrieval of RDF.

Receiving Facilities

26. Evaluate the various types of solid waste receiving facilities.
27. Evaluate segregation of solid waste prior to processing.

Controls

28. Characterize present processing plant electrical control systems.
29. Determine effectiveness of present electrical control systems.
30. Evaluate present spillage and dust control systems.

Fires and Explosion Protection

*31. Study the incidents of fires in waste processing plants.
32. Determine the effectiveness of present fire protection systems.
*33. Study the incidences of explosions in waste processing plants.
34. Determine the effectiveness of present explosion protection systems.
35. Develop improved fire and explosion protection systems for waste processing plants.

Economics

*36. Develop effective and consistent accounting methods for waste processing plants.
37. Compile data on capital costs of solid waste processing equipment.
*38. Determine equipment operating and maintenance costs.
39. Determine economic life of solid waste processing equipment.
40. Perform cost effectiveness analysis of waste processing equipment.

EQUIPMENT TESTS

As a result of the delineation of the research needs for waste processing equipment, a series of in-plant tests were conducted on magnetic separators, an air classifier, air emissions, and shredders.

Magnetic Separator Tests

Two magnetic separator systems were tested. The Outagamie County, Wisconsin system (Figure 1) uses an Eriez Model V separator located over a split hopper with an adjustable blade for impurities control. At Baltimore County, Maryland, the system (Figure 2) is designed around a Dings "Hockey Stick" model separator with a return belt to remove material dropped at the air gap.

The comparison of these two systems, shown in Table 1, indicates that they are very similar. The main difference is the energy consumption; the system at Baltimore County requires more than twice the energy required at the Outagamie county System.

Both systems recovered approximately 80 percent of the available ferrous metal out of the input stream, but the recovered material at Outagamie County contained more impurities (nonferrous) than at Baltimore County. The cleaner material at Baltimore County does not appear to be as much a result **of** the magnetic separator system as the condition of the input material. The particle size after shredding is smaller at Baltimore County,and the material contains twice as much ferrous. At both sites

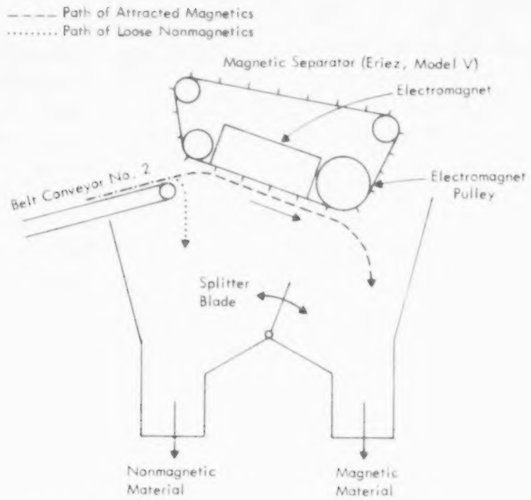

Path of Attracted Magnetics
Path of Loose Nonmagnetics
Magnetic Separator (Eriez, Model V)
Electromagnet
Electromagnet Pulley
Belt Conveyor No. 2
Splitter Blade
Nonmagnetic Material
Magnetic Material

Figure 1 - Magnetic Separator System, Outagamie County, Wisconsin

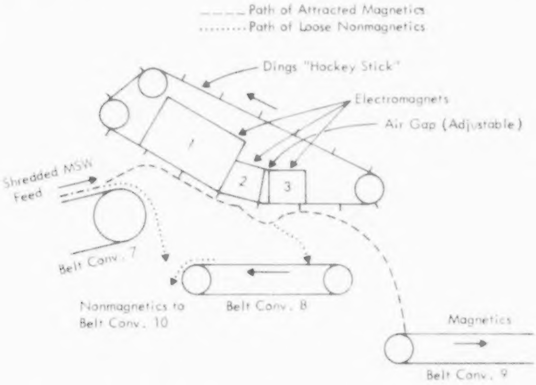

Path of Attracted Magnetics
Path of Loose Nonmagnetics
Dings "Hockey Stick"
Electromagnets
Air Gap (Adjustable)
1
2
3
Shredded MSW Feed
Belt Conv. 7
Nonmagnetics to Belt Conv. 10
Belt Conv. 8
Magnetics
Belt Conv. 9

Figure 2 - Magnetic Separator System, Baltimore County, Maryland

TABLE 1. MAGNETIC SEPARATOR SYSTEMS TESTED

	Outagamie County	Baltimore County
Input rate, tons/hr	26	28
Input belt speed, m/min	65.5	79
Input belt width, cm	110	117
Input belt angle, degrees	30	30
Separator belt speed, m/min	95	117
Separator belt width, cm	91	122
Ferrous in input, %	5.16	10.8
Ferrous recovered, %	81	79
Impurities, %	1.8	0.2
Ferrous in rejects, %	0.9	2.6
Energy consumption, kw	8.3	18.8

observations indicated that the impurities controls were not effective. At Outagamie County, light paper and plastic floated across the splitter blade on air currents, being completely detached from any ferrous material. At Baltimore County, very little material was freed at the air gap; the return belt ran virtually empty.

In both cases, the height of the separator above the input belt was varied in a systematic fashion. At Outagamie County, the length and angle of the splitter blade in the output hopper was changed. Also varied at Baltimore County was the width of the air gap between the second and third magnets.

Table 2 illustrates the effects of changing the variables one at a time. At both sites, there was a linear correlation between the height of the separator above the percent ferrous recovered, the smaller heights produced greater recovery. The splitter blade tests at Outagamie County indicated the closer to the vertical the long blade was positioned, the higher the rate of recovery. This is explained by observations of the recovered ferrous bouncing off of the hopper back plate when it was released from the magnetic field. With the long blade in the vertical position, the least amount of recovered ferrous could fly back into the nonmagnetics chute. At Baltimore County, the test settings of the air gap on the separator did not affect the performance of the system. The recovery rate did not change, and the change in the impurities was only one quarter of a percent.

Air Classifier Tests

The air classifier system at Baltimore County (Figure 3) was tested at a fixed velocity of 5.3 m/s (1,040 ft/min) with input feed rates from 0.51 to 64.00 mg/hr (0.56 to 70.55 tons/hr).

The data from the sample analysis is plotted in Figure 4. The light fraction curve on this graph shows the weight percent of the input material that traveled out of the air classifier with the air. Because the air velocity was held constant, the larger air/solids ratios were obtained by reducing the input feed rates. An operating plant producing RDF will operate as close to the left on the curve as possible without leaving the horizontal portion. At this velocity setting, the air/solids ratio is about 25 and results in a light fraction with a heating value of 15 x 10^6 J/kg and an ash content of 20 percent. The Baltimore County plant includes a trommel after air classification which reduces the fines. These fines constitute a large portion of the 20 percent ash figure because they were not removed from the analyzed samples.

Emissions Tests

Emissions tests were conducted at the Outagamie County and Baltimore County plants to determine the nature of the air emissions produced by processing and handling municipal solid wastes. The emissions of specific interest were particle concentration, particle size, trace metal concentration, and asbestos concentration. Hi-Vol and Acu-Vol samplers were placed near specific pieces of equipment to determine the emissions from that unit.

The highest particulate concentration reading was at the tipping floor at Outagamie County with a reading of 6.617 mg/Nm^3, which is approximately 66 percent of the threshold limit value (TLV) of 10 mg/Nm^3 (Ref. 5). Analysis of the trace metal in the particulates indicates that the amount of toxic metals was well below their respective TLV's. The sample closest to TLV contained a lead content of 0.018 mg/Nm^3 compared to a TLV of 0.150 mg/Nm^3, or approximately a factor of 10 below the TLV. No asbestos was found at Outagamie County, and based on the St. Louis and Houston tests which also showed no asbestos (Refs. 3 and 4), it was decided not to test for asbestos at Baltimore County.

Shredder Tests

Nine shredders were tested for shred

TABLE 2. EFFECTS OF VARIABLE CHANGES

OUTAGAMIE COUNTY

Height (cm)	Short blade angle (degrees)	Recovery efficiency (%)	Impurities (%)	Ferrous in rejects (%)
33	49.5	51	1.79	0.92
35.6	49.5	76	1.50	1.24
38.3	49.5	39	1.69	4.73
33	24.5	71	1.80	1.50
	Long blade angle (degrees)			
33	24.5	80	1.95	0.73
33	37.0	72	2.40	1.70
33	49.5	61	2.41	--

BALTIMORE COUNTY

Height (cm)	Air gap (cm)	Recovery efficiency (%)	Impurities (%)	Ferrous in rejects (%)
46	18	78	0.36	2.15
51	18	73	0.28	4.38
56	18	50	0.22	4.30
64	18	32	0.16	4.98
46	36	79	0.42	2.19
46	18	78	0.36	2.15
46	6	79	0.13	2.64

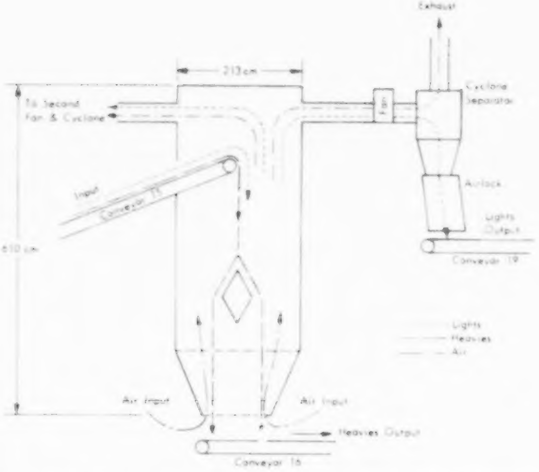

Air Exhaust
213 cm
To Second Fan & Cyclone
Fan
Cyclone Separator
Input
Conveyor 15
610 cm
Airlock
Lights Output
Conveyor 19
Lights
Heavies
Air
Air Input
Air Input
Heavies Output
Conveyor 16

Figure 3 - Air Classifier System, Baltimore County, Maryland

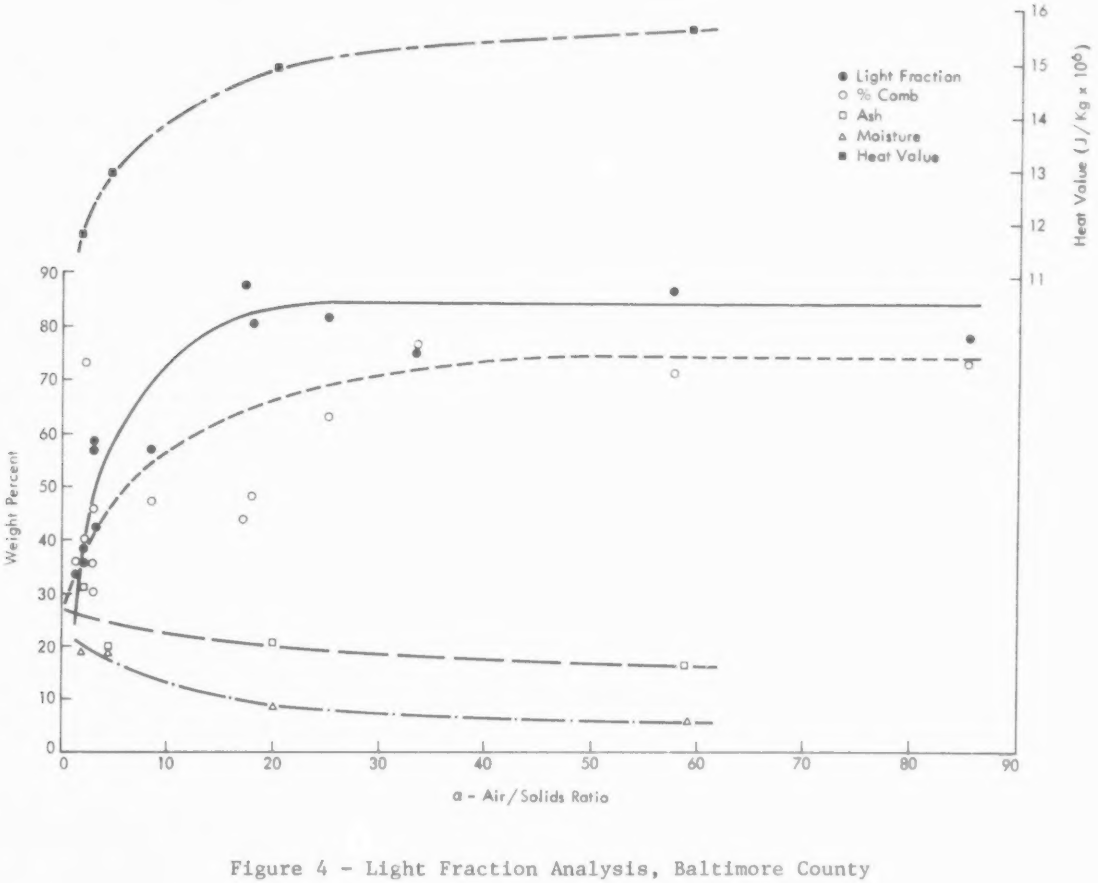


Figure 4 - Light Fraction Analysis, Baltimore County

size, energy consumption, and hammer wear.* The plant locations, manufacturers, numbers and types of shredders tested are given in Table 3. The results of these tests are given in a separate paper at this conference (Ref. 6).

ACKNOWLEDGEMENT

The support of this study by the EPA Municipal Environmental Laboratory, Cincinnati, Ohio, is gratefully acknowledged. The EPA Project Officers were John O. Burkle and Donald A. Oberacker. The cooperation of the plant operators wherein the various tests were conducted made this study possible.

TABLE 3. SHREDDERS TESTED

Location	Manufacturer, Model	Number and Type
Ames, Iowa	American Pulverizer, Model 60-90	2 horizontal hammermills
Baltimore County, Maryland	Tracor Marksmen, Model 860	2 horizontal hammermills
Great Falls, Montana	Heil, Model 42F	1 vertical hammermills
Odessa, Texas	Newell, Model 68	1 horizontal hammermill
Outagamie County, Wisconsin	Allis Chalmers, Model KH 12-8	2 horizontal hammermills
Tinton Falls, New Jersey	Carborundum (Eidal), Model 1000	1 vertical grinder

CONCLUSIONS

The following conclusions may be drawn from this study:

- The magnetic separator systems tested recover approximately the same percentage of the available ferrous metal. However, there are significant differences in the purity of the recovered metal and energy consumption.

- There is a critical air-to-solids ratio for air classifiers. Above the critical ratio, the light fraction separation is maximum and relatively constant; below the critical ratio, the light fraction separation falls off sharply.

- The processing of municipal solid waste does not produce harmful levels of particulates, heavy metals or asbestos.

- There is need for considerable additional research on solid waste processing equipment.

REFERENCES

1. Midwest Research Institute, "Study of Processing Equipment for Resource Recovery Systems," Volume I - State of the Art and Research Needs, Volume II - Field Tests of Magnetic Separators, Air Classifiers, Air Emission, Final Report, EPA Contract No. 68-03-2387, MRI Project No. 4213-D, December 1978.

2. Cal Recovery Systems, Inc., "Evaluation of Shredders Used for Size Reduction of MSW," Final Report, EPA Contract No. 68-03-2589, MRI Subcontract No. 4424-D, to be issued in March 1979.

3. Midwest Research Institute, "St. Louis Refuse Processing Plant: Equipment, Facility and Environmental Evaluation," Final Report, MRI Project No. 4033-L, May 1975.

4. Midwest Research Institute, "Evaluation of Fabric Filter Performance at Browning Ferris Industries Resource Recovery Plant, Houston, Texas," MRI Project No. 4240-L(13), September 1977.

5. American Conference of Government and Industrial Hygienists, "Industrial Ventilation--A Manual of Recommended Practices," 1973.

---

* The shredder tests were conducted by Cal Recovery Systems, Inc., under subcontract with Midwest Research Institute.

6. Cal Recovery Systems, Inc., "Evaluation of Shredders Used for Size Reduction of MSW," Symposium on Gas and Leachate in Landfills and Resource Recovery, Orlando, Florida, March 26-28, 1979.

EVALUATION AND PERFORMANCE OF HAMMERMILL SHREDDERS USED IN REFUSE PROCESSING

G. M. Savage, G. R. Shiflett, L. F. Diaz, and G. J. Trezek
Cal Recovery Systems, Inc.
160 Broadway Suite 200
Richmond, CA 94704

ABSTRACT

This paper presents the results of a comprehensive program to test and evaluate large-scale shredders used for the size reduction of solid waste. In all, four horizontal hammermills were tested at three commercial sites (Appleton, Wisconsin; Ames, Iowa; and Cockeysville, Maryland). Both two-stage size reduction (primary and secondary shredders at Ames) and single-stage size reduction (practiced at Appleton and Cockeysville) were studied as part of this work. Evaluation and interpretation of the data has resulted in the development of analytical relationships among comminution parameters and establishment of levels of performance with respect to energy consumption and hammer wear associated with size reduction of solid waste.

INTRODUCTION

OVERVIEW

Over the past fifteen years the use of shredders in the field of solid waste management has seen steady growth. From first attempts at using size reduction of solid waste as the initial step in the production of a suitable material for composting, the use of shredders has grown into the field of full-scale, integrated resource recovery facilities. In between these events, shredders have seen service in the areas of ferrous scrap recovery from solid waste and treatment of refuse for landfill disposal without the necessity of utilization of cover material.

Shredding (or synonymously, grinding, size reduction, milling, or comminution) of solid waste has taken on an added degree of significance since the initiation of large, full-scale resource recovery operations. For such facilities, size reduction represents the first step in processing the waste stream. Consequently, the unit process of size reduction affects all equipment involved in downstream material handling and separation. In addition, the shredding operation normally accommodates 100 percent of the throughput of waste, whereas other unit processes in resource recovery plants generally handle only particular fractions of the waste stream. As a result, the importance of the unit process of size reduction is generally recognized, albeit poorly understood, by the solid waste industry.

The proliferation of shredders in the solid waste industry has stimulated interest in their operation, evaluation, and performance. For example, criteria for estimation of shredder operation and performance are needed in the initial stage of design of resource recovery plants. Also, the plant manager may wish to know how certain operational changes involving a shredder (such as a change in size of the grate openings or variation in shredder throughput) may affect shredder operation (such as energy requirements and size of product).

The testing and evaluation program

described here was funded by the EPA to extend the present knowledge of size reduction of solid waste. Earlier investigations conducted by two of the authors, Trezek and Savage, and also funded by the EPA, established the key parameters which characterize refuse comminution and the criteria by which they can be evaluated (1,2,3,4). The underlying motivation of the present research is to establish predictive relationships, design criteria, evaluation techniques, and levels of performance for large-scale size reduction equipment. Large scale means shredders with nominal capacities in the range of 20 to 60 tons per hour. The information contained herein has been developed for use and consideration of those associated with solid waste management including shredder manufacturers, plant designers, plant operators, and researchers.

The test program involved detailed measurements of energy and hammer wear associated with size reduction of solid waste, which are the two most important aspects of size reduction due to their effects on operational cost. In order to ascertain relationships involving energy and hammer wear, a rigid, scientific protocol was established and implemented. Cooperation of personnel at each site was instrumental in maintaining a consistent test procedure among plants.

Site-specific test plans were developed and were directed toward assessing the energy consumption and hammer wear associated with shredding. Both operational data and levels of performance were sought for different governing parameters. In order to adequately assess wear and energy consumption, the test program called for collection of samples for determination of product size and moisture content of shredded refuse. In particular, these samples were collected during the interval of energy measurement. Regarding hammer wear, the study concentrated on the evaluation of various hardfacing alloys as well as that alloy typically used at each site. Rates of hammer wear were determined and interpreted.

The shredders that were tested are installed at facilities located in Appleton, Wisconsin; Ames, Iowa; and Cockeysville, Maryland.

SITE DESCRIPTIONS

Appleton: The Outagamie County Solid Waste Shredding Facility located in Appleton, Wisconsin, operates two Allis-Chalmers Model KH 12/18 horizontal hammermills in parallel to shred the approximately 160 tons of refuse received daily. Ferrous material is recovered after shredding using a magnetic belt conveyor, and the remaining shredded waste is compacted into transfer trailers and transported to the landfill.

Ames: The Ames Resource Recovery System in Ames, Iowa shreds approximately 180 tons of refuse per day through two American Pulverizer Model 6090 horizontal hammermills operating in series. Both material and energy recovery are practiced at the Ames plant. Most ferrous material is magnetically separated from the refuse after primary shredding, while the remaining material is subjected to secondary shredding and air classification so as to recover a refuse derived fuel. The refuse derived fuel is pneumatically conveyed to a nearby city-owned power plant where it is co-fired with coal in the utility's boilers. The plant also has the capability of recovering aluminum from the nonferrous heavy fraction.

Cockeysville: The Baltimore County Resource Recovery Facility in Cockeysville, Maryland shreds approximately 320 tons of refuse per day through two Tracor-Marksman Model A60 horizontal hammermills operating in parallel. Although the capability exists for both material and energy recovery, currently only magnetic separation of ferrous material is carried out, and the remainder of the shredded refuse is taken to the landfill.

HAMMER MAINTENANCE PROGRAMS

Two of the sites tested utilize hammer retipping as a means of dealing with hammer wear; the Ames facility is the exception. The Ames operating procedure calls for wearing the hammers in each shredder until they no longer effectively shred refuse. When that point is reached, the hammers are removed, scrapped, and replaced by new hammers.

Contrary to the procedure followed at Ames, the Appleton and Cockeysville facilities utilize hammer retipping as a regular maintenance program. At Appleton, welding wire is used instead of a welding electrode. Stoody 110 is used for building up the hammer surface prior to application of one or two passes of Stoody 134 hardfacing. Stoody 134 is the wire equivalent of a Stoody 2134 electrode, which was used in the wear experiments at Appleton.

MATERIALS AND METHODS

POWER MONITORING INSTRUMENTATION

The power monitoring equipment includes a Scientific Columbus Model DL34-2K5A2-AY-6070 watt/watt-hour transducer, a Houston Instruments Model 3000 chart recorder, and a digital dividing circuit.

The transducer itself is adaptable to single phase, three phase-three wire, or three phase-four wire systems. For multiphase systems, both the voltage and current in each leg are monitored continuously, thus automatically correcting for the power factor. Two output signals are provided by the transducer. The first is an analog current signal which is directly proportional to power (kw). The second transducer output is a digital signal directly proportional to energy consumption. The digital signal from the transducer is sent to the dividing circuit, which counts the pulses and triggers an event marker on a chart recorder after a predetermined number of pulses have accumulated. The divider may be set manually to count between 1 and 9999 input pulses before triggering the event marker.

Since the nominal inputs to the transducer are 120 volts and 6.5 amperes, the appropriate current and voltage step-down transformers that were needed for each test were determined during a survey of each facility prior to the actual test visit.

OTHER EQUIPMENT

A Chronos model 3-ST digital chronometer was used for making any necessary measurements of time. Determination of conveyor belt speeds (for flowrate measurements) and time of sample collection required use of this instrument.

Conveyor belt speeds were determined, when possible, with a Power Instruments Inc., TAK-ETTE model 1707, digital rpm gauge. An alternative method for obtaining the belt speed was to measure the time necessary for the belt to traverse a measured distance, and divide the measured distance by the elapsed time.

In order to obtain size distributions for the shredded refuse samples, the samples were first screened on a set of manually held screens having square wire mesh openings of 20.32, 10.16, 5.08, and 2.56 centimeters. Screening of the undersize from the 2.56 centimer hand held screen was done on a SWECO model LS18533333 Vibro-Energy Rotary Screen. The SWECO was equipped with a series of square wire mesh screens having openings of 2.54, 1.59, 0.95, 0.51, 0.27, and 0.13 centimeters.

SIZE DISTRIBUTION ANALYSIS

Samples of shredded refuse were weighed and dried to a constant weight in a drying room maintained at 22° C and 65% relative humidity. After the samples were dried they were reweighed to permit determination of the moisture content. Size analysis of the samples was performed using manual and mechanical screening. The dried refuse was placed on the largest of the manually held screens and shaken until no further refuse was observed to pass through the screen. The oversize from the screen was collected and weighed, and the undersize was placed on the next smaller screen. The process was then repeated until all four manual screens had been used.

The undersize from the 2.54 centimeter manually held screen was next processed through the SWECO screens. Material was screened on the SWECO screens for a time duration of fifteen minutes.

EXPERIMENTAL PROCEDURES

POWER MEASUREMENTS

Flow rate samples and power level data were collected under a number of different operating conditions for the purpose of characterizing the shredders. To guarantee that the flowrate sample coincided exactly with the interval during which the power was monitored, it was necessary to accurately determine (1) the distance from the center line of the shredder discharge to the center line of the segment of the discharge conveyor from which the flowrate sampled was gathered, and

2) the speed of the discharge conveyor itself. With the shredder sampling distance and conveyor speed known, it was possible to calculate the elapsed time needed for the sample to travel from the shredder to the point of sample collection.

The mass flowrate through the shredder was calculated from the speed of the conveyor belt and the weight of the sample removed from a given distance of belt.

The actual sample used for the size distribution and moisture analysis was obtained by mixing and subsampling of the flowrate sample. In order to ensure that a representative sample for the size distribution analysis was obtained, the size of the subsample was chosen according to the grate spacing of the shredder undergoing testing. In general, the larger the grate spacing, the larger the sample that needed to be gathered. An estimation of the sample size was made using the following table:

TABLE 1. SAMPLE SIZE

Grate Spacing		Sample Size	
cm	(inches)	kg	(pounds)
20	(7.9)	10	(22.1)
15	(5.9)	7.5	(16.5)
10	(3.9)	5	(11.0)
5	(2.0)	2.5	(5.5)

HAMMER WEAR EXPERIMENTAL PROCEDURE

Hammer wear investigations were conducted on base hammer materials as well as on a number of hardfacing alloys. The experimental procedure consisted of cleaning and weighing hammers prior and subsequent to their shredding a measured amount of solid waste. Quantity of hammer material lost and tonnage of refuse shredded were used to ascertain the degree of wear for each type of hammer base material or hardfacing alloy tested. As is common in the industry, the degree of wear is expressed as the weight of material lost per unit weight of refuse shredded.

The general test procedure called for testing hardfacing alloys in each shredder simultaneously thus avoiding as much as possible the influence of uncontrolled variables. Where possible four alloys were tested at one time, one per each row of hammers.

Hammer wear tests were only conducted at the Appleton and Cockeysville facilities. Hammer wear data for the plant at Ames was made available by the City of Ames. All tonnages used for the wear experiments were based upon actual weight measurements.

RESULTS AND DISCUSSION

MOISTURE CONTENT OF SHREDDED REFUSE SAMPLES

Average moisture contents of the shredded samples showed Appleton refuse to be significantly wetter than refuse shredded at either the Ames or Cockeysville facility, namely about 35 percent for Appleton versus roughly 16 percent and 17 percent for Ames and Cockeysville. All moisture contents quoted are on an air dry basis). Although water is sometimes used at Appleton to control dust dispersion, the water spray was turned off five minutes before beginning the test runs. Consequently, the above moisture levels for Appleton are innate moisture contents. Neither Ames nor Cockeysville used a water spray system during the test programs.

The moisture content of Appleton refuse confirmed visual observations that Appleton refuse was typically residential in nature. On the other hand, the refuse processed at Ames and Cockeysville was typical of commercial solid waste.

MEASURED THROUGHPUTS

The primary purpose of this study was to obtain performance and operating data on large-scale shredders, that is, shredders capable of handling large throughputs of solid waste. Shredders evaluated in this study covered the full spectrum of throughput capacity ranging from an average of approximately 20 metric tons per hour (TPH) at the Ames plant to almost 60 TPH at the Cockeysville facility (wet weight basis). The minimum throughput measured during the tests was 3.5 TPH at the Appleton facility while the maximum throughput was 95.7 TPH measured at the Cockeysville plant, again on a wet weight basis. It must be pointed out that both of the above extreme values were special test runs and therefore are not indicative of normal plant operation. These wide variations are a consequence of the attempt to obtain performance and operational data over as wide a throughput base as plant operation would permit.

SIZE DISTRIBUTION OF SHREDDED SOLID WASTE

Each shredder that was tested produced a characteristic size distribution of particles. An overall view of the size distributions that were obtained from the samples that were collected from each shredder is shown in Figure 1. The curves represent an average size distribution for each shredder. The reader is reminded that the input for the Ames secondary shredder is the output from the Ames primary shredder.

ESTIMATION OF SPECIFIC ENERGY REQUIREMENTS

Data collected in these experiments along with that collected by Trezek and Savage (1,2) enable the development of relationships for the prediction of specific energy on a wet weight basis, E_{o_w} (kwh/Ton), as a function of both characteristics (X_o) and nominal (X_{90}) product sizes. The characteristic size and nominal size represent that screen size corresponding to 63.2 and 90 percent cumulative passing, respectively. Here specific energy is defined as the quantity of gross minus freewheeling energy divided by the throughput of material. Average values of E_{o_w}, X_o, and X_{90} calculated from the experimental data are plotted in Figure 2. The trend of increasing energy requirement as a consequence of producing smaller and smaller particle sizes through size reduction is quite apparent.

An attempt to develop a functional relationship between E_{o_w} and the size parameters using standard curve fitting techniques yielded the following equations:

$$E_{o_w} = 17.91X_o^{-0.90} \qquad (1)$$

and

$$E_{o_w} = 35.55X_{90}^{-0.81} \qquad (2)$$

where E_{o_w} is expressed in kwh/Ton and X_o and X_{90} are expressed in cm. The correlation coefficients for equations 1 and 2 are 0.87 and 0.89 respectively.

These equations were developed with the aid of data from facilities handling anywhere from four to ninety metric tons of refuse per hour and consequently represent the full gamut of operating conditions found in actual practice. The equations should be valuable in estimating net power requirements for shredders in general. The term "in general" should not be overlooked since the actual power requirement for a particular shredder is a function of many variables including internal machine configuration, hammer tip speed, throughput, as well as size, composition, and moisture content of the feed.

MOTOR SIZING

With regard to the estimation of the proper size motor for shredding refuse at a specified rate, it must be remembered that gross power requirements are composed of the net power required for size reduction plus the freewheeling power (otherwise known as the idle power or power required when not shredding refuse). Typically, the freewheeling power represents about 10 percent of the full load rating of the motor thus leaving the remaining 90 percent available for size reduction.

An estimation of the net power required to produce a specified particle size can be found by multiplying the specific energy (E_{o_w}) by the anticipated flow rate ($\dot{m}_w$). Dividing the product by 0.9 will then produce a rough estimate of the gross motor power which would be required.

POWER-FLOW RATE-MOISTURE RELATIONSHIPS

To show how flow rate and moisture affect power requirements for the systems tested, a multiple regression analysis was executed for each set of test data. The multiple regression analyses were based on the assumption that the experimental results could be represented by an equation of the form,

$$P_n = a\, m_w^{\;b}(1-MC)^c \qquad (3)$$

where P_n = net power (kwh);
m_w = flowrate of refuse through the shredder (TPH); and
MC = fractional moisture content of the refuse.

as previously ascertained by Shiflett (5).

The exponents "b" and "c" in equation

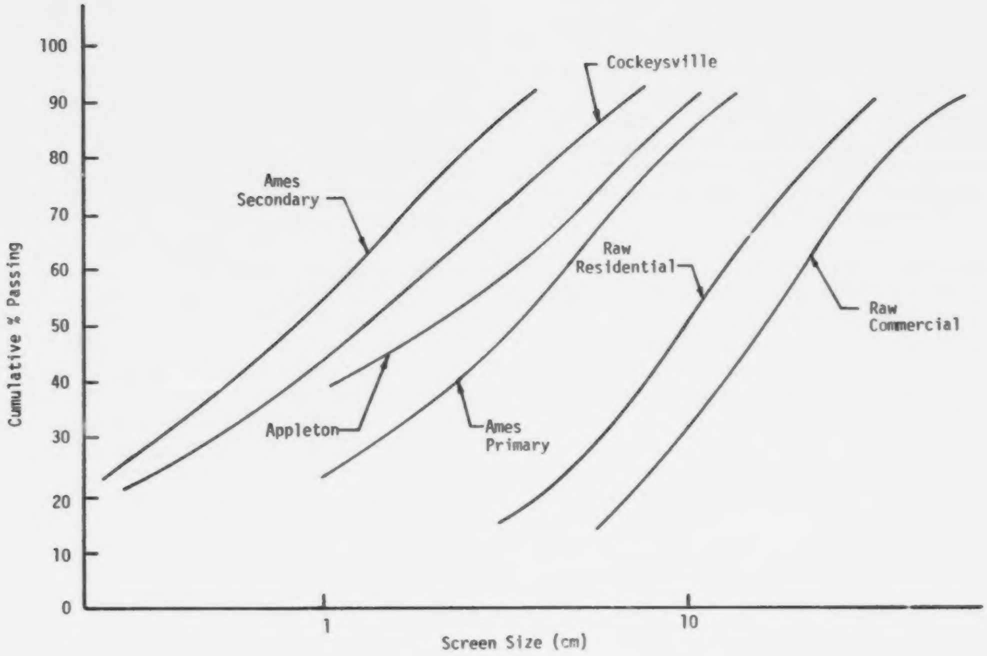


Figure 1. Average size distributions of raw & shredded solid waste.

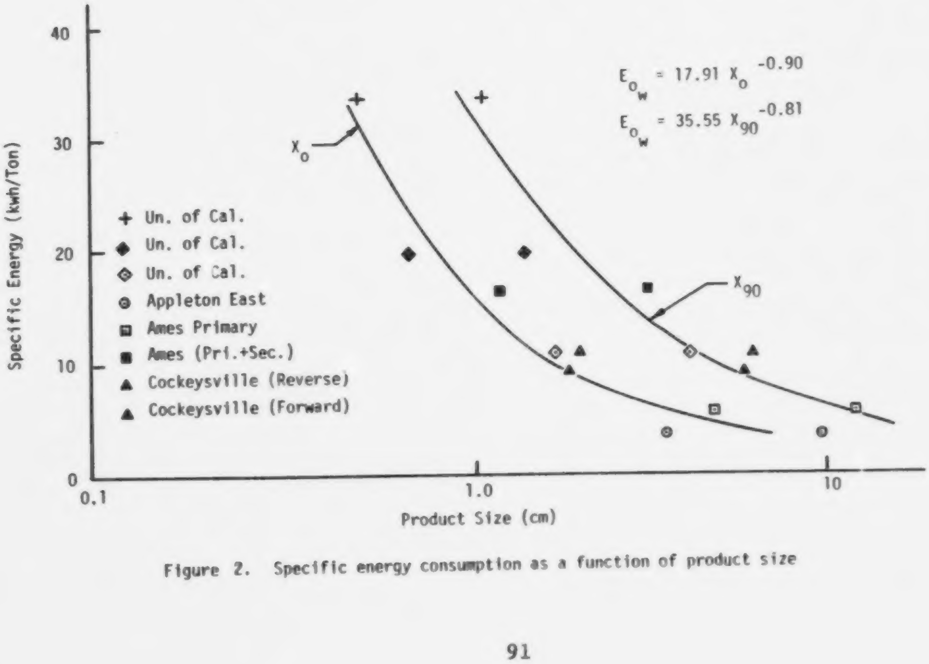


Figure 2. Specific energy consumption as a function of product size

3 determine how power requirements change with flowrate and moisture content, respectively. Positive values for the exponents "b" and "c" indicate that power increases with flowrate but decreases with moisture content. The coefficient "a" determines the magnitude of the power requirements and is influenced by machine parameters, such as size of grate openings, internal geometry, and geometry and number of hammers.

The equations resulting from the regression analyses are presented in Table 2. An examination of the correlation coefficients shown in the table indicates that there is good agreement between the assumed form of the curve and the experimental data.

From Table 2, the calculated values of the exponent "b" can be seen to be positive and close to unity indicating that net power requirements are almost directly proportional to flowrate. The lone exception occurs for the power equation for the Ames secondary shredder in which the exponent "b" is almost two. This high value of the exponent "b" for the Ames secondary shredder may be due to the extremely worn condition of the hammers within the shredder during the test runs. The hammers in all the other shredders that were tested were in good condition.

The calculated values of the exponent "c" ranged from -7.04 to 1.54. Positive values of the exponent "c" obtained for the shredders at Appleton and Cockeysville indicate that power requirements decrease with higher moisture contents. The opposite is true for the primary and secondary shredders at Ames. The negative values of exponent "c" calculated for the Ames shredders indicate that the power increases for increases in moisture content. Negative values for the exponent "c" are contrary to other published data (1,2,4) and are unresolved pending further research.

The large variations in the values of the coefficient "a", that is values spanning the range 0.28 to 47.04, indicate the significant influence of machine characteristics upon power requirements. Some work by Shiflett and Trezek (6) indicates that the amount of material within the shredder at any instant in time, denoted as shredder holdup, may be a basic parameter for ascertaining the influences of machine characteristics upon energy consumption and throughput capacity.

Due to the fact that collection of data for holdup determinations is a disruptive process from the standpoint of testing at an operating facility, we were only able to collect holdup data at the Appleton site. The Appleton data fit the following curves,

$$P_n = 1.60\ H^{0.96} \qquad (4)$$

$$\dot{m}_w = 0.51\ H^{1.04} \qquad (5)$$

with correlation coefficients of 0.82 and 0.90, respectively. These curves are similar in form to those reported in reference (6) indicating the importance of shredder holdup as a key parameter for assessing the effects of machine characteristics upon energy consumption and throughput capacity.

SINGLE VERSUS MULTIPLE STAGE SIZE REDUCTION

Some of the data collected at the Ames and Cockeysville sites can be used to compare single and multiple stage size reduction of solid waste. The comparison involves examination of gross and net power consumption (P_G and P_N, respectively), mass flowrates of refuse ($\dot{m}_w$), and characteristic product size (X_0). For the purposes of comparison of processing alternatives, the criterion of equivalent product size from both single shredding at Cockeysville and secondary shredding at Ames was used. The data allow a comparison for which an average characteristic product size (X_0) of 1.6 cm was calculated.

In order to compare the power requirements of single versus multiple stage size reduction, the moisture content (MC) as well as the product size (already chosen as 1.6 cm) must be specified. For purposes of comparison, the average moisture content was taken as 20.5 percent for a hypothetical refuse processed at Ames and Cockeysville facilities. As previously discussed, net power requirements for size reduction can be expressed by a relation in the form of equation 3.

Since we have specified MC as 20.5

percent, equation 3 reduces to

$$P_N = 0.62\,\dot{m}_W^{\,1.20}\,(0.795)^{-7.04} \qquad (6)$$

and

$$P_N = 0.28\,\dot{m}_W^{\,1.92}\,(0.795)^{-2.84} \qquad (7)$$

for the Ames primary and secondary shredders, respectively, where $\dot{m}_W = 21.6$ T_WPH since that throughput produces the required average characteristic product size of 1.6 cm. For shredder #1 at Cockeysville, the equation for net power (calculated by combining data for both forward and reverse directions of rotation) is

$$P_N = 21.85\,\dot{m}_W^{\,0.90}\,(0.795)^{2.25} \qquad (8)$$

wherein $\dot{m}_W = 52.2$ T_WPH since that throughput produces the desired average characteristic product size of 1.6 cm.

The solution of equations 6,7, and 8 allows calculation of the total net power required to produce the required product size. The total net power required at Ames is 320 kw, and that at Cockeysville is 458 kw. The specific energy (on a wet weight basis, $P_N/\dot{m}_W$) for Ames and Cockeysville are 14.8 and 8.8 kwh/T_W, respectively, refer to Table 3. Consequently, the specific energy required to produce the required product size at Ames is 168 percent of the energy requirement at Cockeysville.

When the freewheeling power of the primary and secondary shredders at Ames, 53 and 41 kw respectively, is added to the net power required for size reduction, the total, or gross, power required is 414. Likewise, when the freewheeling power for the Cockeysville shredder (66 kw) is added to the net power, the gross power required is 524 kw. On the basis of unit mass, the gross energy requirements (gross specific energy) for Ames two-stage shredding and Cockeysville single-stage shredding are 19.2 and 10.0, respectively, refer to Table 3. Based upon producing the same particle size, two-stage size reduction at Ames uses almost twice as much gross energy as single-stage reduction at Cockeysville.

The results presented here must be viewed with caution for two reasons. First of all, to date this type of information on large-scale shredders has only been developed for one specific case. Secondly, it is not known whether or not the shredding lines at Ames and Cockeysville have been optimized to maintain energy consumption at a minimum.

The possibility of optimizing multiple stages of shredding along with methods for establishing optimization have been investigated previously (3). Results reported in reference 3 indicate that multiple stages of size reduction can be less energy intensive than single-stage size reduction under certain circumstances of grate opening size and particle size.

HAMMER WEAR

Results of the hammer wear experiments show a range of 0.013 to 0.106 Kg/T for hammer wear, Table 4. The wide range of values is a result of the numerous hammer materials and hardfacing alloys that were tested.

The greatest rates of wear measured during the tests were sustained by non-hardfaced manganese steel, i.e. bare hammers whose hardness as cast was 14 R_C. For the hardfacing alloys that were tested we found that as the hardness of the alloys increased, the degree of wear correpondingly decreased. The limiting factor at the high range of alloy hardness appears to be chipping of the welds under high impact loads. The trend of decreased hammer wear for harder alloys is apparent if one examines the data from the Appleton west mill and the Cockeysville #1 shredder, Figure 3.

The optimum range of alloy hardness appears to lie within the range $48 \le R_C \le 56$ (shown in Figure 3) with the upper value limited by the chipping tendency of the welds under impact loading. The exact hardfacing alloys for a given shredding operation would have to be determined experimentally by testing a group of different hardfacings having as-deposited hardness values within the optimum range.

The alloys under consideration should be tested simultaneously, for instance one alloy per row of hammers. The importance of simultaneous testing was pointed out from the data collected during

TABLE 2. NET POWER AS A FUNCTION OF FLOWRATE AND MOISTURE CONTENT

Shredder	Power Equation	Correlation Coefficient
Appleton East	$P_n = 6.33\ \dot{m}_w^{0.94}(1-MC)^{1.54}$	0.85
Ames Primary	$P_n = 0.62\ \dot{m}_w^{1.20}(1-MC)^{-7.04}$	0.74
Ames Secondary	$P_n = 0.28\ \dot{m}_w^{1.92}(1-MC)^{-2.84}$	0.93
Cockeysville #1, forward rotation	$P_n = 47.04\ \dot{m}_w^{0.82}(1-MC)^{4.79}$	0.92
Cockeysville #1, reverse rotation	$P_n = 6.40\ \dot{m}_w^{1.18}(1-MC)^{2.01}$	0.96
Cockeysville #1 combined rotation	$P_n = 21.85\ \dot{m}_w^{0.90}(1-MC)^{2.25}$	0.91

TABLE 3. COMPARISON OF SINGLE-STAGE AND DOUBLE-STAGE SIZE REDUCTION

	Cockeysville Single-Stage	Ames Two-Stage
Size of Grate Openings (cm)	20.3x35.6	22.9x25.4 Primary 8.9x12.7 Secondary
Input Particle Size [a](cm)	13	13
Intermediate Particle Size [a](cm)	-	5.0
Final Product Size[a](cm)	1.6	1.6
Flowrate (Tons/Hour)	52.2	21.6
Moisture Content (% air dry)	20.5	20.5
Net Power (KW)	458	320
Freewheeling Power (KW)	66	94
Gross Power	524	414
Net Specific Energy (KWh/Ton)	8.8	14.8
Gross Specific Energy (KWh/Ton)	10.0	19.2

[a] characteristic size: size corresponding to 63.2% cumulative passing

TABLE 4. RESULTS OF HAMMER WEAR EXPERIMENTS

Alloy	Hardness (R_c)	Avg Wt Loss (w_i) (kg/Hammer-Ton)	Wear of Full Hammer Complement (W_o) (kg/Ton)
APPLETON			
EAST MILL			
Stoody 2134	48	9.44×10^{-4}	0.023
WEST MILL			
McKay 48	38	4.84×10^{-4}	0.023
McKay TiC	45	3.30×10^{-4}	0.016
Stoody 2134	48	3.60×10^{-4}	0.017
Amsco Super 20	56	2.73×10^{-4}	0.013
AMES			
Manganese Steel	14	5.50×10^{-4}	0.026
COCKEYSVILLE			
SHREDDER #1			
Mangjet	21	2.88×10^{-3}	0.069
Abrasoweld	36	1.87×10^{-3}	0.045
McKay 55	49	0.89×10^{-3}	0.021
Faceweld 12	57	1.57×10^{-3}	0.038
SHREDDER #2			
Manganese Steel	14	4.40×10^{-3}	0.106

the Appleton wear experiments. The test results for Stoody 2134 for the east and west mills show wide disparities for wear, 0.023 and 0.017 kg/Ton, respectively (Table 4). The differences in the rates of wear possibly point out the effects of refuse composition and operational variables, such as hammer geometry, base material of hammers, rpm, etc. Simultaneous testing eliminates these variables and allows comparison of different hardfacing alloys without biasing from uncontrolled variables.

Comparisons of hammer wear data among sites must take into account the degree of size reduction since operating experience has shown that wear increases as product size of shredded refuse decreases. In addition to size of the product, size of the feed material also may have a bearing on the degree of hammer wear. The fact that Appleton refuse tended to be more residential in nature than that at either Ames or Cockeysville implies that the characteristic size of the feed for the Appleton experiments should be on the order of 12.7 cm. On the other hand, the commercial character of the waste encountered at Ames and Cockeysville implies that the feed size should be larger, on the order of 20.3 cm. These are average values for raw residential and commercial waste which are based upon previous experience and several waste composition and sizing studies conducted by Cal Recovery Systems.

In order to account for variations in the size of the feed material and the shredded product size among different sites, a parameter termed the degree of size reduction (Z_o) is introduced. This term is defined as

$$Z_o = (F_o - X_o)/F_o \qquad (9)$$

where F_o and X_o are characteristic feed size and product size, respectively.

Values of the degree of size reduction range from a value of zero corresponding to no size reduction to a maximum limit of 1.0 corresponding to a product size of zero, or in other words an infinite amount of size reduction. The latter limit is, of course, unachievable in actual practice.

Normalization of the wear data collected at Appleton's west mill and Cockeysville's shredder #1 is demonstrated in Figure 4, using average Z_o values and data from the two curves drawn in Figure 3. Although only two points are present for each curve, the general trend of increased wear at large values of Z_o can be discerned. Also, the parametric effect of alloy hardness (R_c) is apparent, i.e. for a particular value of Z_o, wear is greatest for the softest hardfacing alloy.

The general conclusion that can be drawn from the data in Figure 4 is that hard alloys yield significant reductions in hammer wear, for example, on the order of 60 percent if an alloy with a hardness of 56 R_c is used instead of an alloy with a hardness of 28 R_c. A 60 percent reduction in wear means that the hammers coated with the harder alloy could be used about 1.8 times longer than those coated with the softer alloy.

SUMMARY

This study of large-scale shredders has served to establish levels of performance that can be expected from horizontal hammermills with respect to size reduction of solid waste. Due to the intrinsic difference among shredders and the diverse conditions under which they operate, predictive relationships were developed to allow interpretation of the experimental results such that all shredders could be compared on the basis of producing an equivalent particle size. Earlier studies (1,2,3,4) had established: 1) the important governing parameters that describe the process of size reduction and 2) the methods of evaluating shredder performance. Results of the present study serve to substantitate the utility of the evaluative criteria and the methods of analysis that were established during earlier investigations.

The information developed in this study provides a data base that up to this point in time had been lacking for shredders operating in the field. Special emphasis was placed on investigating methods of minimizing energy consumption and hammer wear as well as determining the magnitude of any possible improvements. Concurrently, governing relationships among the key parameters of size reduction were developed to describe the shredders that were tested.

The need for further research has also been established as a consequence of this

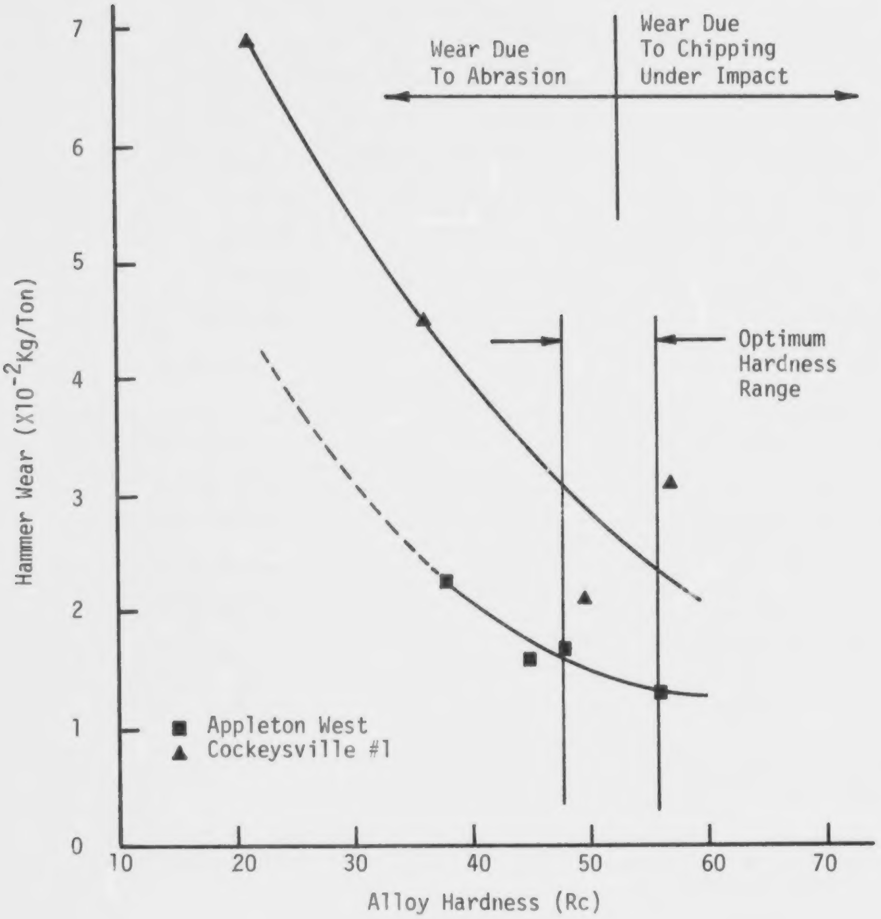


Figure 3. Hammer Wear as a Function of Alloy Hardness

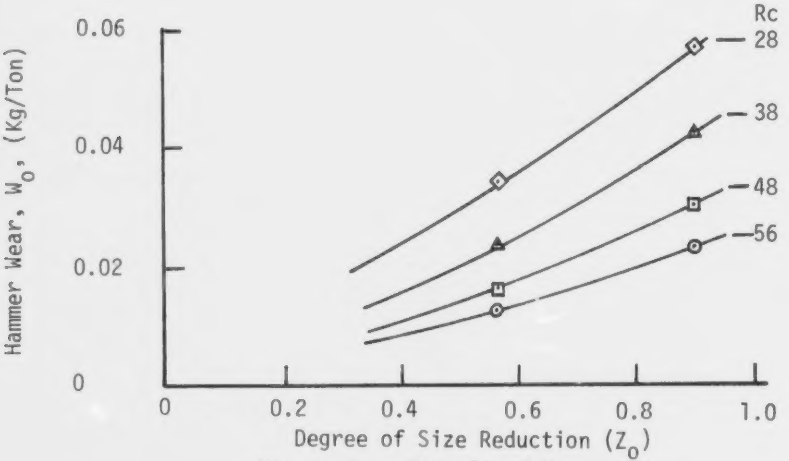


Figure 4. Normalized Hammer Wear

program of shredder testing and evaluation. There are two areas in particular that need further attention. The first area involves optimization of shredding lines, which ultimately would serve to minimize energy consumption. A test conducted at a site employing two-stage size reduction would serve to widen the data base for establishing criteria for optimizing shredder lines. If such a test could include several grate bar changes in both the primary and secondary shredders, the optimum grate bar configuration for each shredder could be established and the appropriate methods of optimization could be identified.

The second area requiring attention deals with the effect of machine characteristics, such as size of grate openings, internal geometry, and geometry and number of hammers upon specific energy requirement, throughput, and particle size. This second area is directly concerned with shredder design and manipulation of particle size. Although some predictive relationships have been developed as a consequence of this work, the mere fact that some of the coefficients and exponents in the equations show a wide range of values portends that the universal governing relationship for size reduction has not been established. Up to this point in time, the effects of machine characteristics (grates, internal geometry, number of hammers) have not been studied in the field. Such an investigation would serve to coalesce our present knowledge of size reduction and subsequently lead to the possible development of a universal governing relationship.

ACKNOWLEDGEMENT

This research was supported by the U.S. Environmental Protection Agency, Municipal Environmental Research Laboratory, Contract Number 68-03-2589, Mr. Donald Oberacker, project officer.

The test program was conducted under subcontract to Midwest Research Institute, Mr. David Bendersky, project manager.

REFERENCES

1. Trezek, G. J. and Savage, G. M., Significance of Size Reduction in Solid Waste Management, EPA-600/2-77-131, July 1977.

2. Trezek, G. J. and Savage, G. M., Size Reduction in Solid Waste Processing, Progress Report 1973-1976, Report to the Environmental Protection Agency prepared under Grant No. EPA R 801218.

3. Savage, G. M., Trezek, G J., and Shiflett, G. R., Size Reduction in Solid Waste Processing - Fine Grinding, Progress Report 1976-1978, Report to the Environmental Protection Agency prepared under Grant No. EPA R 803034.

4. Trezek, G. J. and Savage, G. M., Results of a Comprehensive Refuse Comminution Study, Waste Age, July, 1975.

5. Shiflett, G. R., A Model for the Swing Hammermill Size Reduction of Residential Refuse, D. Eng. dissertation, University of California at Berkeley, 1978.

6. Shiflett, G. R. and Trezek, G. J., Parameters Governing Refuse Comminution, Resource Recovery and Conservation, In press, 1979.

DEVELOPMENT OF CONTINUOUS ACID HYDROLYSIS PROCESS FOR THE UTILIZATION OF WASTE CELLULOSE

Walter Brenner, Barry Rugg, Robert Stanton
Peter Armstrong and Kuan-Ming Ang
Department of Applied Science
New York University
New York, New York 10003

Charles Rogers
Solids and Hazardous Waste Research Division
U.S. Environmental Protection Agency
Cincinnati, Ohio 45268

ABSTRACT

Cellulosic wastes are being re-evaluated in terms of an underutilized renewable resource for both energy production and materials recovery, rather than a solid waste disposal problem. Acid hydrolysis is a potentially attractive route for upgrading the value of cellulosic wastes by converting them to glucose. The glucose can then serve as an alternate feedstock to petrochemicals for fuels, intermediates and the synthesis of single cell protein. New York University has carried out considerable work on this developing technology with emphasis on two crucial steps, namely, a cost effective cellulose waste pretreatment and a high sugar yield acid hydrolysis. Extensive experimental investigations for achieving these objectives are described. These studies led to the development of a continuous acid hydrolysis process in order to optimize the acid hydrolysis of waste cellulose to glucose. The development of a continuous acid hydrolysis process based on the application of a twin screw reactor is discussed and preliminary information is presented on the establishment and operation of a continuous acid hydrolysis process facility.

INTRODUCTION

Interest in the possible industrial use of waste biomass for both materials and energy recovery has been greatly stimulated by the convergence of two apparently unrelated problems, i.e., the steadily rising price of fossil fuels and the even greater magnitude of the solid waste disposal problems. Currently employed methods for dealing with these solid wastes are admittedly increasingly inadequate for cost effective utilization of their latent energy values, material and especially for cellulose which comprises a major portion of solid wastes. Waste cellulose conversion to glucose via acid hydrolysis offers attractive possibilities for more effective usage of a large and continuously-growing yet grossly underutilized national resource. As is shown in Figures 1 and 2 the glucose from cellulosic wastes could be employed for the manufacture of many volume chemicals which are presently obtained from petrochemical feedstocks.

The potential quantities of chemical feedstocks, etc., which could be obtained from waste cellulose conversions are quite significant. Assuming a realistic 32% available cellulose in the wastes and only 16% conversion to ethylene, the estimated 1550 million tons of farm waste alone would yield 28 million tons ethylene per annum1). This represents twice the U.S. consumption of this basic building block in 19753). The economic feasibility of waste cellulose utilization is of course, greatly dependent on both waste collection and processing conversion costs as well as the quantities and values of the end products obtained.

HISTORICAL REVIEW

Acid hydrolysis of cellulose has been extensively studied for the better part of a century, particularly in connection with manufacturing ethanol from wood wastes. The discovery that cellulose can be hydrolyzed in acid solutions and converted to its monomer, glucose, was first reported by Bracconnot 160 years ago, in 1819. The reaction has been experimentally investigated ever since then, mostly on a strictly empirical basis, in order to develop a cost effective process for producing sugar from wood wastes and other sources of waste cellulose.

Research and development on the acid hydrolysis of wood wastes was particularly active during the first part of this century both in the U.S. and Western Europe. These acid hydrolysis studies went far beyond the laboratory scale up to the construction and operation of limited production facilities for glucose and ethanol in the U.S. and in Western Europe8). The U.S.S.R. and Japan have also been very active in the field of wood saccharification.

The growing interest in the utilization of waste cellulose for energy production and materials recovery has led to the recognition that the present state of knowledge in this area is largely empirical and that more basic information could be helpful in the development of a more cost effective hydrolysis process. Both economic and technical reasons favor a dilute acid hydrolysis of waste cellulose to be conducted at high temperatures and for short time periods so as to maximize the glucose yield. Determination of the reaction kinetics of the waste cellulose conversion to glucose is necessary for establishing the optimal reaction conditions and has therefore been studied in some detail.4)5)6)

While the acid hydrolysis of cellulose is heterogeneous, it can be regarded as a homogeneous reaction provided that the cellulose reactant is dispersed in the form of fine particles, e.g. 200 mesh or less. A kinetic scheme for the acid hydrolysis of crystalline wood was proposed by Seaman as long as 30 years ago. This scheme was used to effectively model the hydrolysis of cellulose in wood chips and likewise cotton linters.

Porteous and later Fagen et al. applied Seaman's model to describe the formation of glucose from commercially available waste paper.4)5)6) Porteous predicted a maximum sugar yield of 55% with 0.4% acid at 230°C. The Fagan experiments were carried out with rather small samples (0.5 gms) of ball milled Kraft paper. Such kinetic studies are now deemed of considerable value for the development of improved process designs and economic data of waste cellulose to glucose and/or ethyl alcohol production facilities.4)5)

The kinetically predicted maximum sugar yields assume that the cellulose reactant has appropriate chemical reactivity for the acid hydrolysis. The technical problems of cellulose hydrolysis are to a great extent due to the fact that this is not the case. The lack of an adequate amount of chemical reactivity in cellulose is called lack of accessibility. This is related to the highly inert character and crystalline organization on a molecular level of the highly molecular weight cellulose and also the presence of lignin. Hydrogen bonding almost certainly plays a very important role in the structure of cellulose and may be a key factor in explaining its chemical inertness.

Over the years, a very extensive amount of R & D has been concerned with the development of the both technically effective and economically viable cellulose pretreatments. The basic approach has been to reduce the crystallinity and disrupt the hydrogen bonding thus rendering it more accessible to hydrolytic depolymerization reactions.7) This should make it possible to approach the predicted glucose yields more closely. Many different pretreatments have been proposed and a considerable number of them have been experimentally investigated.

In general, mechanical treatments such as, intensive ball-milling to sizes below 60 mesh, have been found to be technically possible, but at an estimated cost of 6¢/lb which is economically prohibitive. Employment of high energy ionizing radiation has been shown to be at least equally effective when the cellulose is exposed to dosages in the order of 100 megarads.18) Sugar yields as high as 70%

based on the available cellulose have been reported for thusly irradiated wood pulp after dilute acid hydrolysis. The cost of such large dosages of ionizing radiation is however, too high for industrial usage. Other less effective pretreatments which have been experimentally studied, include expending of the cellulose to various chemical reagents, heat, etc.

Development of lower cost pretreatment technology such as would produce mechanical and/or chemical size and/or crystallinity reductions, for maximizing cellulose accessibility, is recognized as an essential requreiment for an industrially acceptable waste cellulose-glucose conversion process. The pretreatment must furthermore be combined with a high productivity acid hydrolysis process so as to optimize the conversion of the pretreated waste cellulose to glucose.

EXPERIMENTAL BATCH SCALE ACID HYDROLYSIS STUDIES

Experimental investigations on the dilute acid hydrolysis of waste cellulose to glucose have been carried out at the Department of Applied Science of New York University over the past four years. The waste cellulose feedstock employed in these studies was primarily used newspapers. A limited amount of work was also conducted with wood waste. The experimental work was an evaluation of the cost effectiveness of various pretreatments for enhancing the accessibility of the cellulose; determination of the optimum reaction conditions for maximizing the sugar yields; techniques for glucose recovery; also fermentation of glucose to ethanol.

The hydrolysis experiments were initially carried out batchwise in a 1 liter stirred autoclave equipped with appropriate accessories such as electrical heating units, a quick discharge ball valve for removal of the reaction mixture after acid hydrolysis from the autoclave, etc. The data obtained with the batch 1 liter stirred autoclave reactor experiments were then analyzed with respect to the glucose yield at various reaction conditions. This was followed by scaling up to a 5 liter stirred autoclave reactor again with suitable accessory equipment. Quite extensive experimental work was carried out with this larger reactor in order to obtain a better understanding of scale up and other problems for the dilute acid hydrolysis reaction of the waste cellulose. Stainless steel equipment was employed for all of these experiments.

Waste newspapers were first subjected to various preselected pretreatments and then charged in the form of water slurries with known cellulose concentrations to a stirred autoclave reactor. These cellulose slurries were then heated with continuous stirring to predetermined reaction temperatures and pressures. The required amount of acid was added only when the desired reactive conditions had been attained. Considerable emphasis was placed on the rapid quenching of the reaction products following completion of a carefully timed hydrolysis in order to optimize glucose recovery by minimizing the formation of acid decomposition products of glucose. Cellulose concentrations in the slurries ranged from 5 to more than 20 wt%.

The batch scale hydrolysis experiments with the two differently sized stirred stainless steel autoclave reactors were encouraging in that they showed that glucose yields up to 50% or more of the available cellulose values charged could be obtained. It was furthermore found that economically acceptable yet technically effective pretreatments are possible for obtaining such glucose yields. The optimum reaction conditions were found to be temperatures of around 220°C-230°C and reaction times of less than 30 seconds with about 1 wt% of sulfuric acid. They agree rather well with the results of the kinetic rate studies which were previously reported by Porteous and Fagan.6)9)

Various pretreatments for the waste newspaper feedstock were experimentally investigated in order to enhance the cellulose accessibility to the dilute acid. These pretreatments consisted of Wiley mill grinding, industrial dry grinding, hydropulping, hydropulping with ferric ion/hydrogen peroxide presoak and hydropulping followed by exposure to various dosages of ionizing radiation. Figure 3 compares the effectiveness of these pretreatments on glucose yield for 450°F acid hydrolysis reactions.

The technically most effective pretreatment is seen to be the irradiation of the hydropulped used newspaper feedstock. The irradiations were carried out at ambient temperatures and in the presence of air with a 3 MeV Dynamitron electron beam accelerator at Radiation Dynamics, Inc., Plainview, L. I., N.Y. service center. While irradiation dosages ranging from 5 to 50 megarads were investigated, the 10 megarad dosage was selected as most cost effective. The combined costs of this hydropulping/irradiation pretreatment have been conservatively estimated at 0.3 - 1.1 c/lb waste cellulose feedstock. Figure 4 shows the significant improvement in the glucose yield obtained by irradiating the hydropulped waste cellulose.

The irradiation treatment itself was accomplished rather simply. The hydropulped waste newspapers were placed in the form of slurries in polyethylene bags and the bags were heat sealed. Each bag contained about 20 lbs of a hydropulped waste newspaper slurry of known cellulose concentration. The bags were then placed on a conveyor which moved past the beam of the Dynamitron electron beam accelerator. The total dosage per pass was 5 megarads.

The effect of changing the hydrolysis reaction temperatures and times on glucose yield were experimentally investigated in considerable detail for used newspapers which had been subjected to this combination hydropulping/irradiation pretreatment. Typical results of a series of scale experiments which were carried out in the larger 5 liter stirred autoclave reactor, are depicted in Fugure 5. The data show that 450°F temperatures and quite short reaction times in the 20 second range were optimal for this dilute acid hydrolysis.

Preliminary exploratory studies have been carried out on recycling the unreacted cellulose for obtaining additional glucose product. The unreacted cellulose was recovered from the reaction slurry by filtration and then rehydrolyzed under analogous reaction conditions. Table 1 shows typical initial results. The additional amount of glucose obtained decreases sharply in terms of total glucose yield with the second recycle. An alternative procedure would be mixing of the unreacted cellulose with fresh used newspaper feedstock in various proportions. The cost effectiveness of such recycling techniques is under study.

More recently the use of various organic acids in place of the sulfuric acids has been investigated for this acid hydrolysis. Preliminary data for the glucose yields obtained with different organic acids are shown in Figure 6. Maleic acid was found to be surprisingly effective in enhancing the glucose yield compared to the other acids studied to date. Table 2 shows that maleic acid catalyzed hydrolysis works best with hydropulped and irradiated newspapers. Use of this acid which is of course more expensive than sulfuric acid, can be expected to ameliorate the equipment corrosion problems and possibly also the rate of high temperature degradation of the glucose product.

The conversion of the glucose product to ethyl alcohol has also been studied on a limited scale. Conventional fermentation techniques were utilized for these experiments. No particular difficulties were encountered as might be expected in view of the broad knowledge of glucose to ethanol fermentations. Ethanol product characteristics have been determined in accordance with established procedures.

CONTINUOUS ACID HYDROLYSIS STUDIES

Considerable effort is being devoted to an investigation of possible continuous processing technology being clearly preferable to batch reactions for industrial scale waste cellulose to glucose conversions[12-16]. This work has resulted in the design and costing of a continuous waste cellulose to glucose pilot plant with a 1 ton/day capacity. This pilot plant is based on the concept of employing hydropulping and possibly, irradiation for pretreating a waste cellulose feedstock; and a screw conveyor and reactor device for continuously reacting pretreated cellulose in an aqueous slurry at suitably elevated temperatures.

The key to successful operation of a continuous acid hydrolysis process is the design of the hydrolysis reactor. This reactor has to be capable of feeding, conveying and discharging hydrolyzable cellulosic materials continuously while maintaining appropriate temperatures in a reaction zone. Because this hydrolysis requires exposure of the reactor components to dilute acids at high temperatures and pressures, all materials of construction have to be resistant to corrosion, especially in the reaction zone.

A Werner & Pfleiderer ZDSK53 (53mm) twin screw extruder (Werner & Pfleiderer Corp., Waldwick, N. J.) was selected because of its capacity for conveying, mixing and extruding the required amounts of cellulosic feedstock. This machine allows accurate control of temperature, pressure, residence time, etc. within the previously established acid hydrolysis operating conditions. The key working elements, intermeshing twin screws, eliminate materials build-up in the processing section and make feasible close control of residence time, etc., with intensive mixing.

For continuous processing this reactor must be coupled with an appropriate feeding mechanism for cellulose slurries and a discharge system for reacted material while maintaining pressure and temperature in the reaction zone. A steam jacketed crammer feeder made by Werner & Pfleiderer Corp., was interpreted with the twin screw extruder so as to maximize throughput with preheating as required. A Kamyr intensive service 2" ball valve (Kamyr Valve Co., Glens Falls, N.Y.) was selected as the major component for the design of the discharge system. Additional ancillary equipment includes a high pressure steam generator for supplying energy to the reactor, an acid pump capable of high pressure injection of acid and a slurry pump for introducing feedstock into the crammer feeder.

This equipment was obtained and installed at the Antonio Ferri Laboratories of New York University (Westbury, L.I.N.Y.). Figure 7 shows a floor plan of the facility which includes space for pulp storage, routine analysis and an office. A photograph of the twin screw reactor together with the crammer feeder and the discharge ball valve (without actuator) is shown in Figure 8.

Hydropulped recycled newspaper feedstock is obtained in slurry form (10% solids content) from the Garden State Paper Company (Garfield, N.J.) Optionally it is irradiated at the Radiation Dynamics, Inc., Plainview, L.I., N.Y. service center with a dosage of 10 Megarads. This pulp feedstock is introduced into the reactor by means of the above mentioned slurry pump and crammer feeder. The waste cellulose is then conveyed with heating by the twin screws into the reaction zone where the required amount of acid is introduced. Hydrolysis then takes place at a predetermined temperature and pressure and the product is promptly discharged.

Two fundamental problems in this reaction scheme have been identified, both relating to maintenance of pressure in a flow reactor. Firstly, pressure has to be maintained at the inlet to prevent egress of material through the crammer feeder. The solution has been found to be development of a dynamic seal in the form of a densified plug of material within the inlet zone of the reactor. Secondly, continuous discharge of the hydrolyzed material has to be accomplished while maintaining pressure. This has been accomplished by the design of a discharge system which includes a hydraulically powered activator for the Kamyr valve.

Preliminary shakedown of this continuous acid hydrolysis system has been completed. Experiments are underway to characterize the system and to optimize reaction conditions for maximum glucose yield. Work has commenced on a study of the material and energy balances of the system.

SUMMARY AND DISCUSSION

Continuous acid hydrolysis is a potentially attractive technology for energy production and materials recovery from cellulosic wastes via glucose. Considerable progress has been made in the development of such a process. A 1 ton/day pilot plant has been constructed based on a twin screw hydrolysis reactor. Technical feasibility has been established. Characterization and optimization studies are in progress. Consideration is being given to utilizing the technology for methane production as the final end product.

ACKNOWLEDGEMENT

This study was supported by the U.S. Environmental Protection Agency under Grant No. R805239-010 under the direction of Charles Rogers. The authors would like to thank Mr. Larry Perlmutter and Mr. Dennis Nadis for their contributions in the design and assembly of the continuous reactor laboratory.

REFERENCES

1. Baker, P. and Ruggeberg, W.H.C., "Glucose Isomerization - Possible Impact On Chemical Utilization of Carbohydrates", presented at the Spring National American Chemical Society Meeting, New York, N.Y April 1976.

2. Bracconot, H., Am. Chem. Phys., 12 (2) (1819) (Fr.).

3. Chemical Engineering and News, January 10, 1977 and October 12, 1977.

4. Converse, A.I., et a., "A Laboratory Study and Economic analyses for the Acid Hydrolysis of Cellulose in Refuse to Sugar and Its Fermentation to Alcohol", Final Report under PHS Grant No. UL-00597-02. Thayer School of Engineering, Dartmouth College, Hanover, N.H. (1971).

5. Fagan, R.D., Converse, O. and Grethlein, H.E., "The Economic Analysis of the Acid Hydrolysis of Refuse", Thayer School of Engineering, Dartmouth College, Hanover, N.H. (1970).

6. Fagan, R.D., Grethelein, H.E., Converse, A.O. and Porteous, A., Environmental Science and Technology, 5, 545 (1971).

7 Millet, M.A., et al., "Physical and Chemical Pretreatments for Enhancing Cellulose Saccharifications", presented at the Symposium on Enzymatic Conversions of Cellulosic Materials: Technology and Applications", sponsored by U.S. Army Natick Laboratories, September 8, 1975, Newton, Mass.

8. Lloyd, R.A. and Harris, J.F., "Wood Hydrolysis for Sugar Production", FPL Rpt. No. 2029, March 1955, Forest Products Laboratory, U.S. Department of Agriculture, Madison, Wisconsin

9. Porteous, A., "Towards a Profitable Means of Municipal Refuse Disposal", American Society for Mechanical Engineering Publ., 67-WAPID-2, (1967).

10. Saeman, J., Industrial Engineering Chemistry, 37, 43 (1945).

11. Ware, S.A., "Fuel and Energy Production by Bioconversion of Waste Materials", EPA Report (600 76-148, August 1976, Municipal Environmental Research Laboratory, U.S. Environmental Protection Agency, Cincinnati, Ohio 45268.

12. Personal discussions, N. Kronlund, Black Clawson Company, Fall 1976.

13. Personal discussions, S. Huss, Garden State Paper Co., Saddle Brook, New Jersey, Fall 1976.

14. Personal discussions, M. Cleland, Radiation Dynamics, Inc., Melville, Long Island, New York, November 1976.

15. Rogers, C., Brenner, W., and Rugg, "Radiation Treatment of Solid Wastes", presented at the First Radiation Processing Conference, June 1976 (Cerromar Beach, Puerto Rico; to be published).

16. Rogers, C., Unpublished Report, November 1976, EPA Solids and Hazardous Wastes Laboratory, Cincinnati, Ohio.

17. Winters, O., and Eng., M.T., Hydrocarbon Processing, p. 125, et al., November 1976.

18. Saeman, J. and Millett, M., "Effect of High-Energy Cathode Rays on Cellulose", Industrial Engineering Chemistry, 44, 2848 (1952).

19 Cleland, M.R., Thompson, C.C., and Malone, H.F., "The Prospects for Very High-Power Electron Accelerators for Processing Bulk Materials", Transactions of the First International Meeting of Radiation Processing, Radiation Physics and Chemistry, Vol. 9, Nos. 4-6 pages 547-566.

20. Grethlein, H.E., "Comparison of the Economics of Acid and Enzymatic Hydrolysis of Newsprint", Biotechnology and Bioengineering, Vol. XX, pp. 503-525 (1978).

TABLE 1

EFFECT OF RECYCLING ON GLUCOSE YIELD FOR DILUTE SULFURIC ACID HYDROLYSIS AT 450°F

RUN	PERCENT GLUCOSE YIELD
450°F Acid Hyrdolysis	51
With one recycle	59
With two recycles	63

TABLE 2

MALEIC ACID CATALYZED HYDROLYSIS OF WASTE CELLULOSE (FEEDSTOCK: GARDEN STATE PAPER CO. USED NEWSPAPERS)

FEEDSTOCK PRETREATMENT	PERCENT SOLIDS IN DRAG	VOLUME ACID* CC	TIME SEC	TEMPERATURE°F	PERCENT GLUCOSE YIELD
Hydropulping	5.1	80	60	450	32.5
Hydropulping + irradiation	5.2	80	60	450	60.9
Hydropulping	5.0	160	40	450	30
Hydropulping + irradiation	4.8	160	40	450	58.6
Hydropulping	11.0	150	40	420	16.5
Hydropulping + irradiation	10.1	150	40	420	24.5
Hydropulping	5.0	80	60	450	32.5
Hydropulping + irradiation	4.7	80	60	450	58.7

---

* 40% concentration

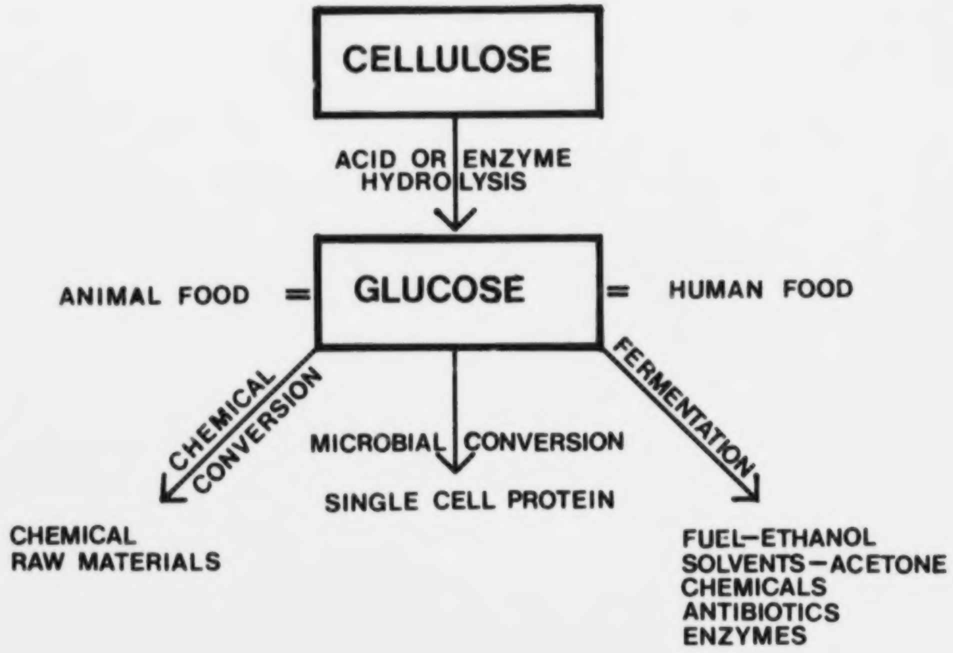

CELLULOSE
ACID OR ENZYME HYDROLYSIS
GLUCOSE
ANIMAL FOOD =
= HUMAN FOOD
CHEMICAL CONVERSION
MICROBIAL CONVERSION
FERMENTATION
CHEMICAL RAW MATERIALS
SINGLE CELL PROTEIN
FUEL–ETHANOL
SOLVENTS–ACETONE
CHEMICALS
ANTIBIOTICS
ENZYMES

FIG.1: WASTE CELLULOSE UTILIZATION ROUTES

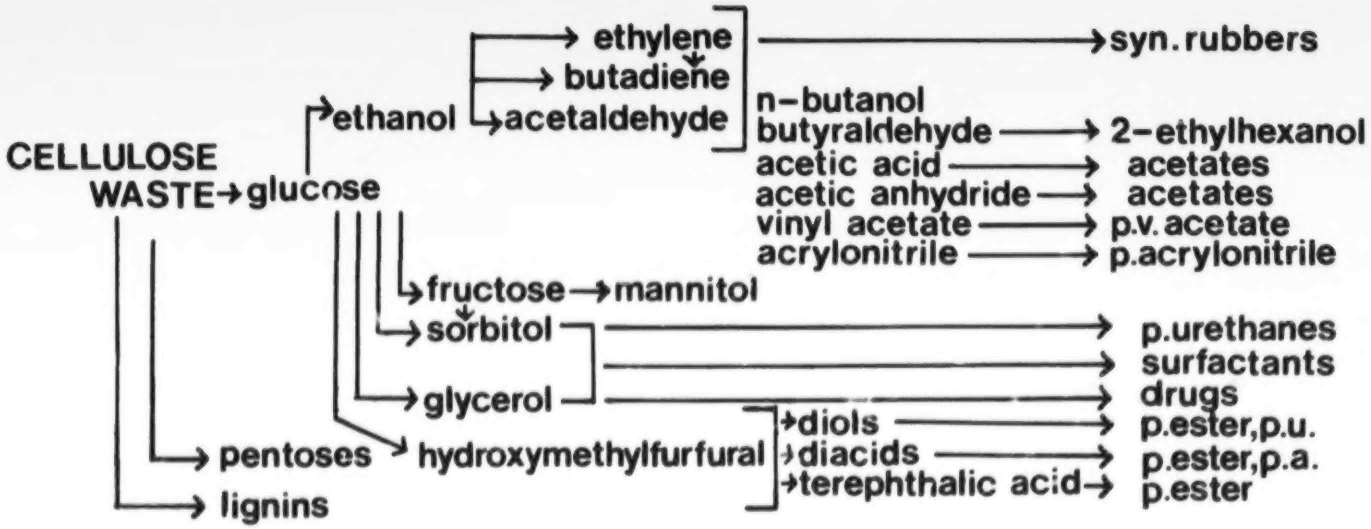

CELLULOSE WASTE
glucose
ethanol
ethylene
butadiene
acetaldehyde
syn. rubbers
n-butanol
butyraldehyde
2-ethylhexanol
acetic acid
acetates
acetic anhydride
acetates
vinyl acetate
p.v. acetate
acrylonitrile
p.acrylonitrile
fructose
mannitol
sorbitol
glycerol
p.urethanes
surfactants
drugs
diols
p.ester,p.u.
diacids
p.ester,p.a.
terephthalic acid
p.ester
pentoses
hydroxymethylfurfural
lignins

FIG.2: POSSIBLE ROUTES TO PETROCHEMICALS FROM CELLULOSIC WASTES

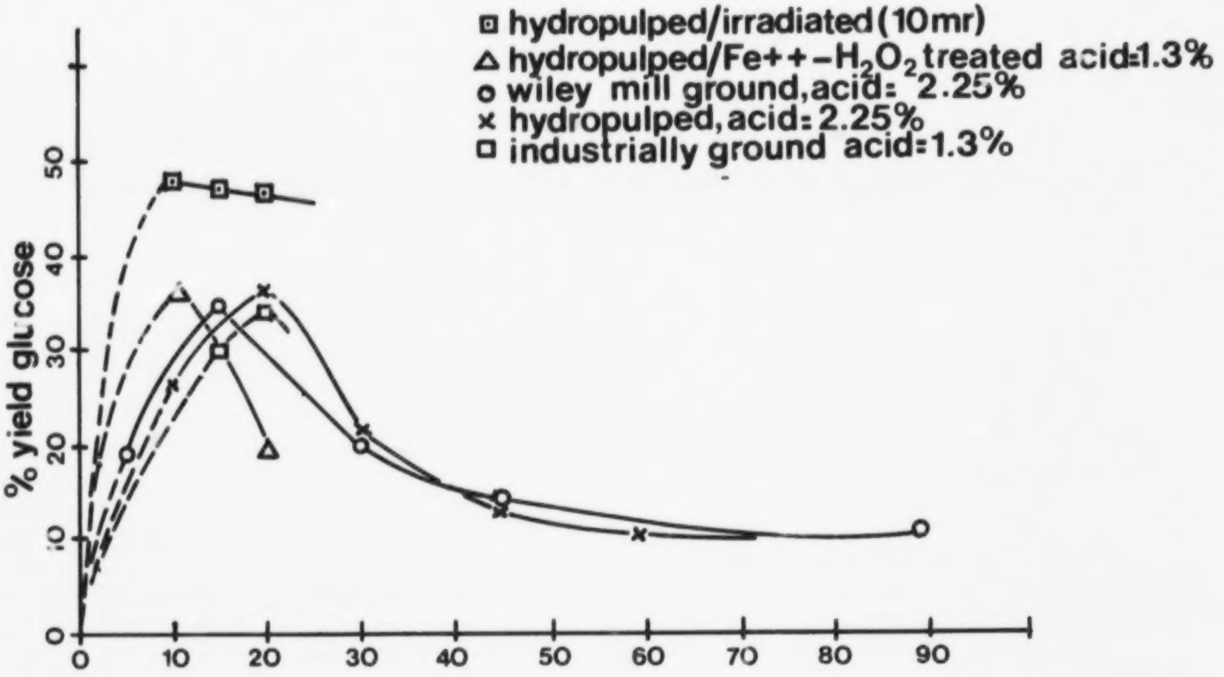


FIG.3: % GLUCOSE YIELD VS REACTION TIME FOR ACID HYDROLYSIS OF GARDENSTATE PAPER AT 450° FOR VARIOUS PRETREATMENTS

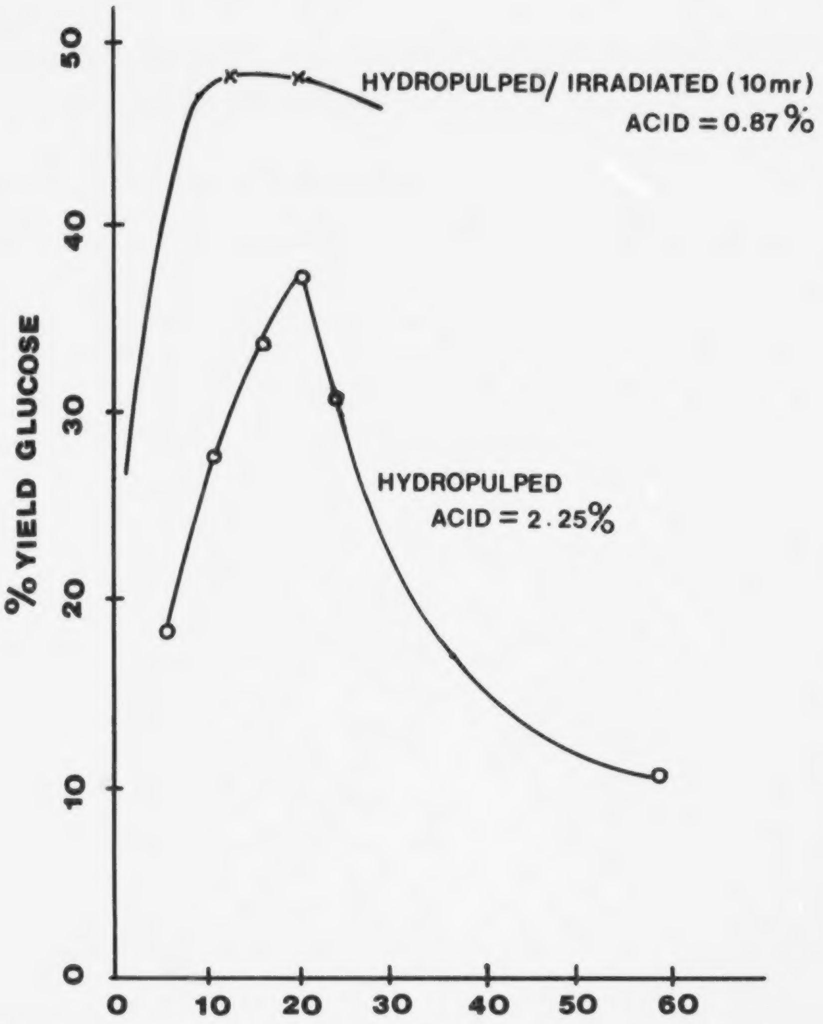


FIG. 4: % GLUCOSE YIELD VS REATION TIME FOR ACID HYDROLYSIS OF GARDENSTATE PAPER AT 450°F

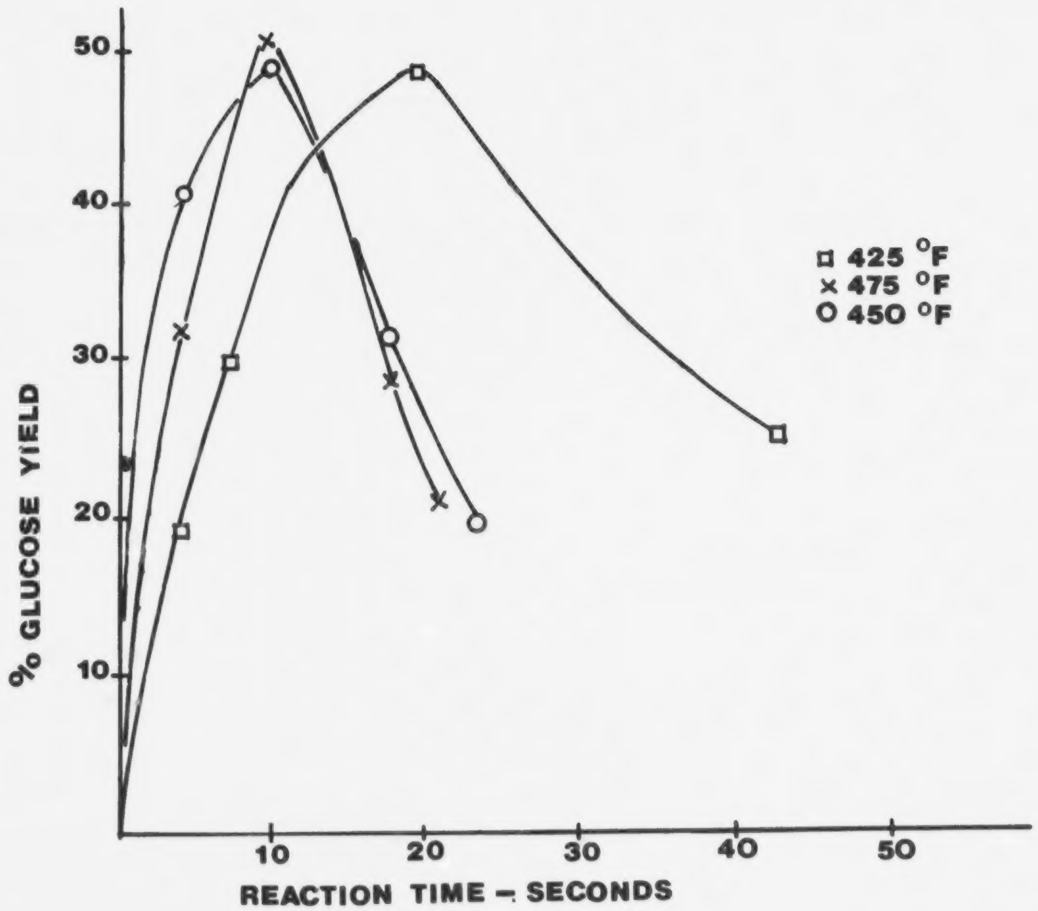


FIG. 5: ACID HYDROLYSIS OF HYDROPULPED AND IRRADIATED (10 MR) USED NEWSPAPERS EFFECT OF REACTION TEMPERATURE ON GLUCOSE YIELD

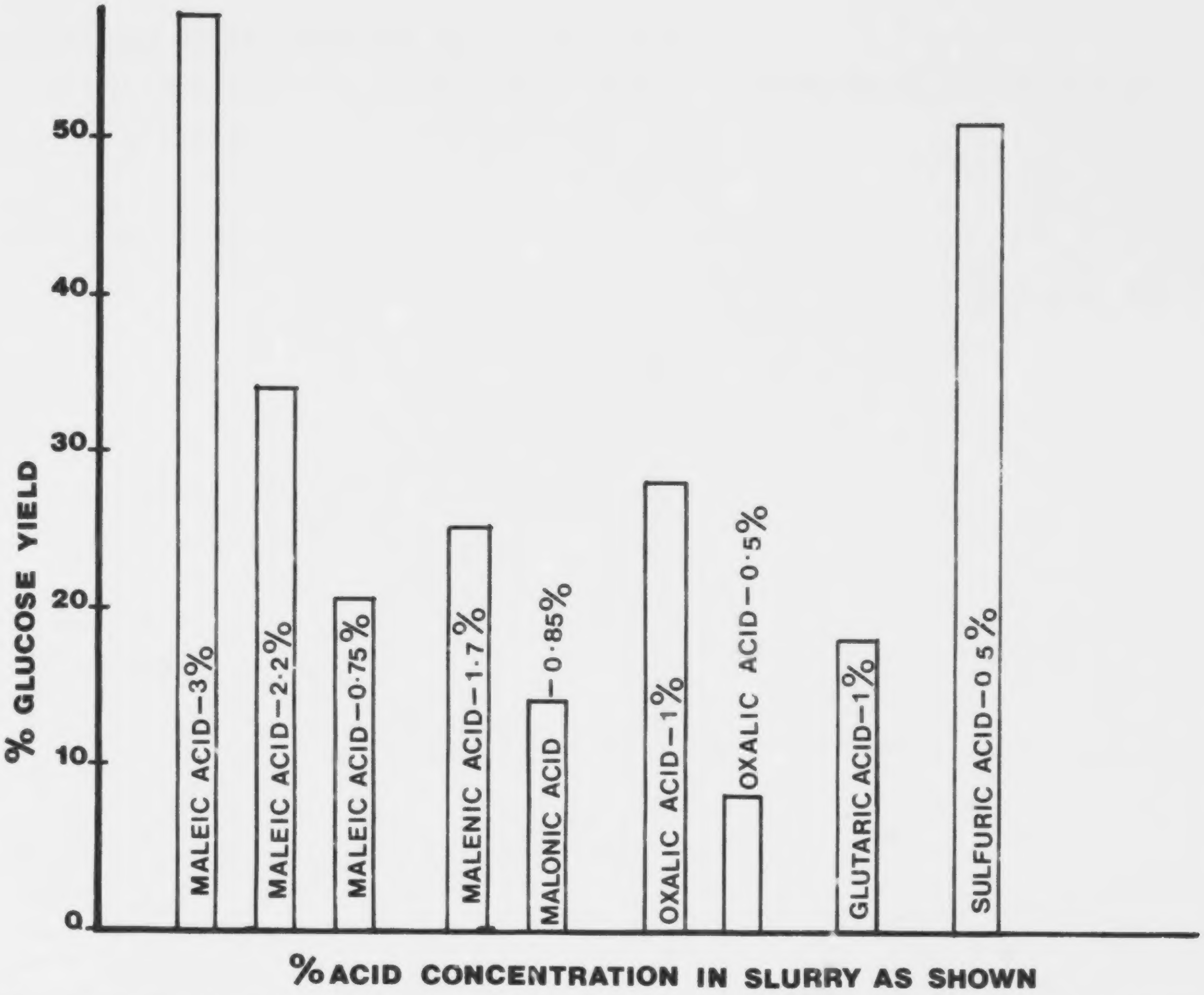


FIG.6: HYDROLYSIS OF HYDROPULPED AND IRRADIATED (10 MR) USED NEWSPAPERS WITH ORGANIC ACIDS EFFECT OF SELECTED ORGANIC ACIDS ON MAX. % GLUCOSE YIELD AT 450°F

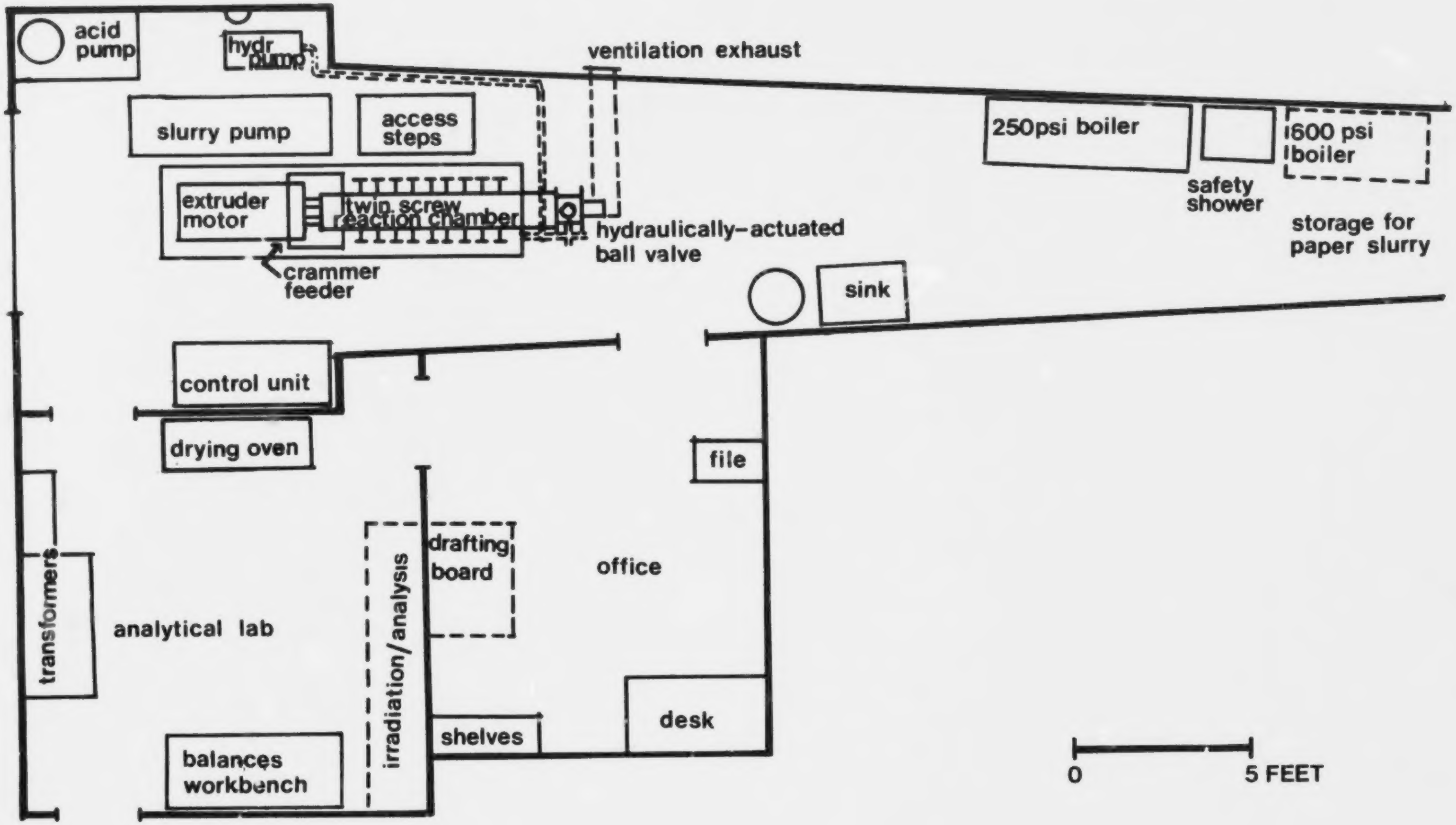

acid pump
hydr pump
ventilation exhaust
slurry pump
access steps
250psi boiler
1600 psi boiler
safety shower
storage for paper slurry
extruder motor
twin screw reaction chamber
hydraulically-actuated ball valve
crammer feeder
sink
control unit
drying oven
file
drafting board
office
transformers
analytical lab
irradiation/analysis
shelves
desk
balances workbench
0
5 FEET

FIG.7: NYU/EPA ACID HYDROLYSIS WASTE CELLULOSE TO GLUCOSE CONVERSION CONTINUOUS PILOT PLANT

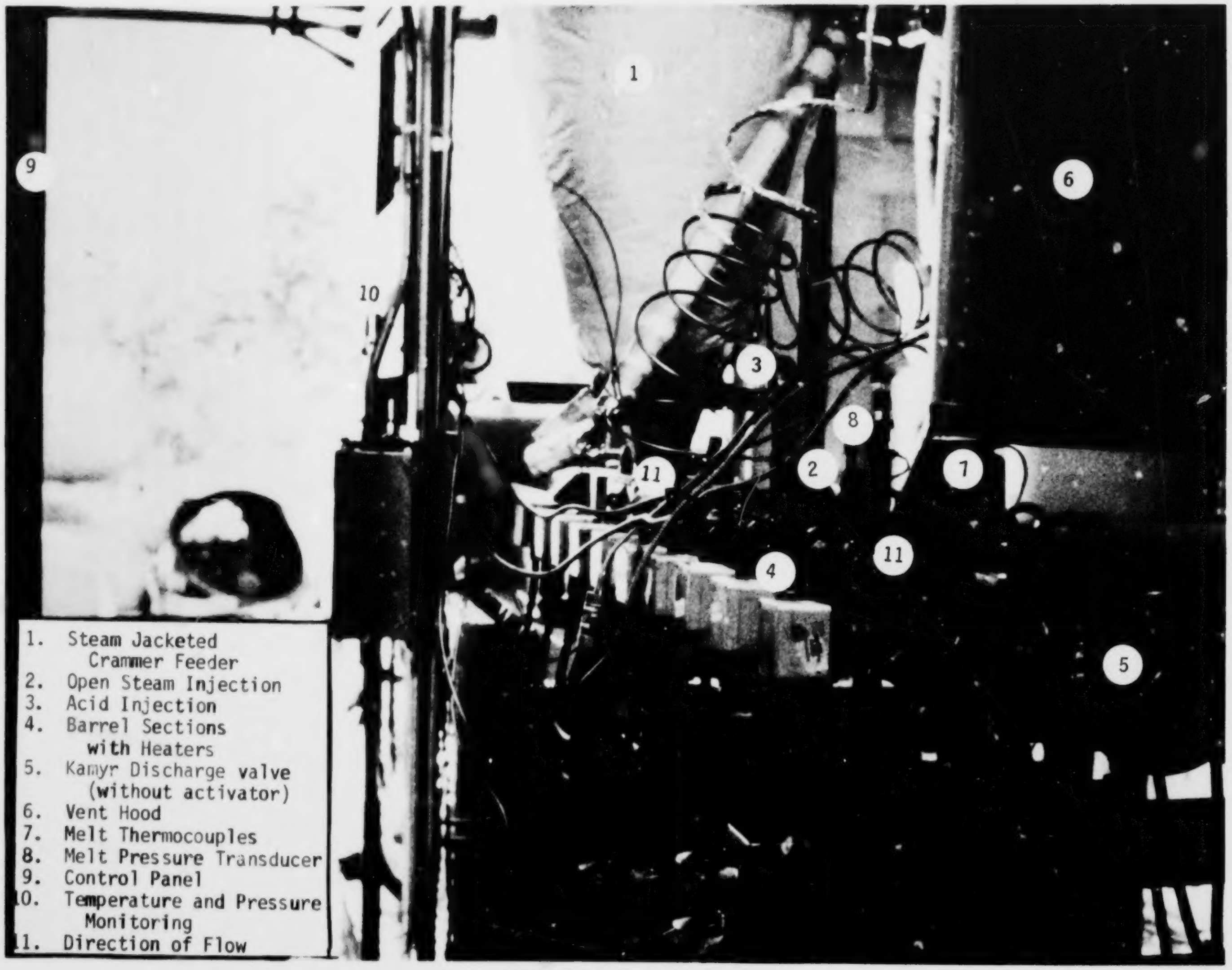

1
9
6
10
3
8
2
7
11
11
4
5
1. Steam Jacketed Crammer Feeder
2. Open Steam Injection
3. Acid Injection
4. Barrel Sections with Heaters
5. Kamyr Discharge valve (without activator)
6. Vent Hood
7. Melt Thermocouples
8. Melt Pressure Transducer
9. Control Panel
10. Temperature and Pressure Monitoring
11. Direction of Flow

Fig. 8. Werner & Pfleiderer Twin Screw Extruder Reactor

PRODUCTION OF METHANE FROM ACID HYDROLYSATES OF CELLULOSE WASTES

V. R. Srinivasan

Department of Microbiology, Louisiana State University, Baton Rouge, LA 70803

ABSTRACT

Anaerobic digestion of acid hydrolysates of cellulose presents certain advantages over direct conversion of cellulose to methane. Lack of variation of the composition of the feedstock and the absence of suspended particles make it easier to optimize the environmental conditions for continuous production of methane at shorter residence times. Short residence times may lead to design of digesters of small size and increased productivity. Experiments are in progress for continuous generation of methane from glucose with mixed population of micro-organisms enriched from rumen.

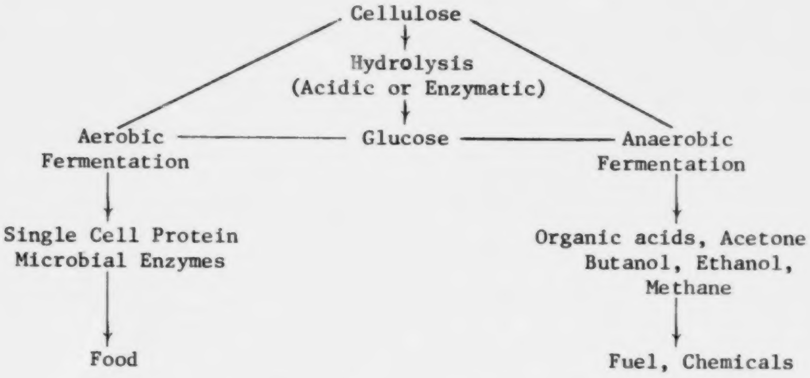
INTRODUCTION

Solid wastes are generated in increasing amounts in todays affluent and consumer-oriented society. Most estimates place the rate of increase in municipal solid waste generation at about 4% per year while the rate of population growth per year is only about 1% (1). The need for conservation of our natural resources and the problems of abatement of environmental pollution have been primarily responsible for the increased number of investigations on the recovery of resources and conversion of solid wastes into usable energy or other products. The composition of municipal solid wastes varies to a limited extent, however, nearly 50% of the waste is usually cellulosic paper products. The heating value of the waste is generally between 3000-6000 BTU per pound. Some of the new technological developments in solid waste management include: (a) the use as a supplemental fuel in the coal-fired boilers (b) pyrolysis-destructive distillation at high temperatures (1000-2000 C) in an oxygen-deficient atmosphere to generate valuable gaseous mixtures and liquids containing organic chemicals, (c) process for conversion of garbage and combustible refuse into synthetic petroleum yielding more than one barrel of crude oil per ton of refuse, (d) microbial degradation of cellulosic portion of the refuse for obtaining useful products.

MICROBIAL DEGRADATION OF CELLULOSE

Biodegradation of cellulose may be carried out by several methods using different genuses or species of microorganisms. Fungi, yeasts as well as bacteria can be used either singly or as a stable-mixed culture of organisms. Cellulose may be fermented aerobically or anaerobically dependent upon the type of desired products to be generated. The aerobic process is more efficient for the growth of organisms while anaerobic fermentation produces valuable organic chemicals. Approximately 1.2 moles of ATP are required to fix 1 mole of carbon in the cell aerobically while 7-10 moles of ATP are necessary for fixing 1 mole of carbon in the cell by anaerobic processes. Looking at it from the point of view of carbohydrate utilization, less than 20% of the carbohydrate present in the nutrients, is utilized for the generation of the cell mass during anaerobic fermentation (2). Some of the different products which may be obtained by microbial fermentation of cellulose may be summarized schematically as in Fig. 1.

will mainly discuss the background on methanogenesis, advantages of our strategies in the production of methane and finally our accomplishments during this period.



Our laboratory has been interested in the microbial fermentation of cellulose for the past several years. We have successfully completed laboratory investigations on the optimization of conditions for continuous production of single cell protein from cellulose. Quite recently under a contract from USEPA R805239-02 we have started our investigations on the production of methane from acid hydrolysates of cellulose. The objectives of our studies may be outlined as follows:

1. To obtain a stable mixed population of a methanogenic organism with other compatible anaerobic organisms.
2. Studies on methanogenesis by the mixed culture from glucose under different environmental conditions such as pH and temperature.
3. Experiments on the optimization of the nutrients in the medium (such as N, P, etc.) and dilution rate for continuous production of methane and maximizing productivity based on glucose.
4. Studies on the production of methane with different concentrations of reduced sugars obtained by acid hydrolysis of paper wastes, by the method developed by Drs. Rugg and Brenner at New York University, N.Y.

Since these studies have been started only a couple of months ago, this report

BACKGROUND ON METHANOGENESIS

Production of methane by anaerobiosis is essentially a two step process. First, biodegradable organic materials such as carbohydrates and proteins are broken down to organic acids, CO_2 and H_2. Then in the second step methanogenic organisms convert the end-products of the first step into CH_4 utilizing the energy produced during conversion for their growth. Weimar and Ziekus have reported that Methanosarcina barkerri grown in the presence of H_2/CO_2 alone or mixotrophically with methanol converted 81% and 79% respectively of substrate carbon into methane (3). Methane-producing bacteria are not capable of generating methane directly from complex carbohydrates or lipids. This in any type of biogas digester for the production of methane, one has to deal with diverse groups of organisms interacting with one another. The terminal reaction in the synthesis of methane during anaerogiosis may be expressed as

$$4H_2A + CO_2 = 4A + CH_4 + 2H_2O$$

where H_2A may represent the range of methanogenic substrates such as formic acid, acetic acid or methanol or even hydrogen (4). The response of the methanogenic organisms to any change in the environment in the reactor is more sluggish than other interacting organisms. Hence, it becomes necessary to maintain the optimum environments in the reactor for the growth of methane bacteria. Considerable amount of information has been published recently about the growth and physiology of different species of methane bacteria. Extensive investigations are being carried out on methanogenic bacteria isolated from diverse environments, such as coastal sediments, lake muds, decayed tree barks, anaerobic digestors and cattle rumen. Some generalizations as to the characteristics of methanogenic organisms can be made from these studies. Methane bacteria are obligate anaerobes. They are the most sensitive to oxygen of all the organisms known at present. The optimum temperature of growth for these organisms depends upon habitat of the organism from which it was originally isolated. There are thermophilic and mesophilic methanogens. The organisms in general are able to grow and produce methane only in the range of p^H's 6 to 7.0. Thus it is imperative that either a good buffering system has to be present in the reactor or p^H must be controlled automatically for the reactor to be operative. It is also advantageous to adjust the carbohydrate feed in such a manner that acids are not formed at a rate greater than the rate of which they are utilized by the methanogens. This is one of the many factors involved in sub-optimal operation of a biogas generator. Relatively slow rates of conversion of organic substances to methane, necessitates the constuction of large production of methane. Morris, et al. have summarized some of the pertinent factors which influence the anaeoribic fermentation in biogas generators (Table 1).

USE OF ACID HYDROLYSATES OF CELLUSOSE AS SUBSTRATES FOR METHANE PRODUCTION

It is common observation in the anaerobic digesters in biological waste treatment the normal operating process at times, suddenly goes "sour" as a response to environmental change. This is generally due to increased content of carbohydrates in the feed. Once such phenomenon occurs, it is several weeks before the start-up and normal functioning of the digestor is related. The foremost advantage of using reducing sugars obtained by acid hydrolysis of cellulose as substrates for the biogas generator is maintaining a reasonable constant feed composition. This is an important factor if the digester is operated for extended periods of time without frequent shut-downs. If cellulose to glucose by cellulose is used directly in the digester, then the solubilazation of cellulose to glucose by celluloytic organisms becomes the limiting step which requires long residence times for digestion. Moreover the particulate materials settle down to the bottom of the reactor, and the microorganisms have atendency to adhere to the suspended particles. This results in inefficient transfer of nutrients to the organisms and which can be avoided by soluable carbohydrates. Such difficulties are not insurmountable as shown by the design and operation of anaerobic digesters using agricultural farm residues or animal feed lot waste. However, from the author's experience with cellulose fermentation, it is fair to state that optimazation of a fermentation process is much less complicated with soluble substrates than with solids. Optimization of kinetics of methane production is a key step in deciding

Table 1 (5)

Environmental and Operational Factors Effecting Anaerobic Fermentation

Environmental Factors	Operational Factors
p^H	Composition of Organic Substrates
Alkalinity	Retention Time
Volatile acid concentration	Concentration of substrate
Temperature	Organic loading rate
Nutrient Availability	Degree of mixing
Toxic Materials	Heating and heat balance

whether the process will be economically viable.

EXPERIMENTAL

Several pure strains of methanogenic organisms were obtained from Dr. Wolin at New York Public Health Laboratories, Albany, NY. The organisms are maintained and routinely grown in the medium of the following composition: 100 ml of the medium contain 0.5 g glucose:0.5 g trypticase:0.2 g yeast extract:4 ml of 0.6% K_2HPO_4:4 ml of a solution containing KH_2PO_4 (0.6%) $(NH_4)_2SO_4$ (0.6%) NaCl (1.2%) $NgSO_4 \cdot 7H_2O$ (0.245%) and $CaCl_2 \cdot 2H_2O$ (0.159%). The medium also contained 5 ml of 8% Na_2CO_3 and 0.05 g $Na_2S \cdot 9H_2O$.

In order to obtain stable population of mixed organism with methanogenetic ability, enrichment of organisms from the rumen of a fistulated cow was executed. Rumen fluid was filtered through cheese cloth and initial enrichment was accomplished using Difco "Thioglycollate medium". Organisms were transferred serially after 3 days of growth under oxygen-free nitrogen containing 5% CO_2. Methane was determined by gas chromatography. After nearly 20 transfers, the mixed population still retained the ability to produce methane. With this inoculum, methanogenesis was studied in different media. The organisms are also grown in media without glucose. In the absence of glucose methane production was higher. This was found to be due to drastic changes in the pH. In 24 hours pH changed from 7.2 to 4.5. Hence, the organisms are maintained at present in a medium containing proteose peptone as the carbon source and yeast extract for the growth factors. A continuous culture of the mixed population was set up in order to circumvent the inhibition of methane production by sudden changes in the pH. Also, the technique will be used to select a population which will generate methane from glucose alone. The same apparatus will be used to optimize the environmental factors for methanogenesis from glucose. The apparatus consists of a 400 ml wide-mouthed bottle as the culture vessel placed in a water-bath whose temperature was kept at 38°C. The inflow of the nutrient medium was controlled by a peristaltic pump (Harvard Apparatus Co.) The gas outlet also served as the exit tube for the excess liquid in the reactor, thus keeping the volume constant. The outlet was connected to a siphon with a head space which split the gas and liquid streams. The whole apparatus inclusive of the nutrient vessel was kept under oxygen-free nitrogen. The different connections were made with heavy-walled butyl rubber tubings in order to ensure no diffusion of atmospheric oxygen. The nutrient medium per liter consists of the following composition: Glucose 10 g., yeast extract 0.2 g: $(NH_4)_2SO_4$ 0.3 g:K_2HPO_4 0.07 g; $NaH_2PO_4 \cdot H_2O$ 0.02 g, $MgCl_2 \cdot 6H_2O$ 0.06 g and trace elements (Ca^{++}, Fe^{++}, Mn^{++}, and Zn^{++}). The medium also contained 0.5 g of $Na_2S \cdot 9H_2O$ and resazurin 0.002 g.

At present we are still in the process of enriching and stabilizing the population of organisms in the above medium and we propose to collect quantitative information in the next several weeks.

REFERENCES

1. Rimberg, D. (1975) Municipal Solid Waste Management. Publ. Noyes Data Corporation. pp. 3-18.

2. Hobson, P. N. (1971) Rumen Microorganisms. Progress in Industrial Microbiology. 9:41-77.

3. Weimar, P. J. and J. G. Zeikus. (1978) One carbon metabolism in methanogenic bacteria. Arch. Microbiol. 119:49-57.

4. Kirsch, E. J. and R. M. Sykes. (1971) Anaerobic Digestion in biological waste treatment. Progress in Indust. Microbiology. 9:155-237.

5. Morris, G. R., W. J. Jewell and R. C. Loehr. (1977) Anaerobic fermentation of animal wastes: Design and operational criteria in Food, Fertilizer and Agricultural Residues. Ed. R. C. Loehy. Publ. Ann Arbor Sci. Michi. pp. 395-413.

STABILIZATION AND CHARACTERIZATION OF PYROLYTIC OILS

Malcolm B. Polk and Metha Phingbodhipakkiya
Department of Chemistry
Atlanta University
Atlanta, Georgia 30314

ABSTRACT

Capillary gas chromatographic, liquid chromatographic and gas chromatographic - mass spectrometric analysis procedures have been developed for the pyrolytic oils. The major components identified were: ethanol; 1-butanol; isobutanol; acetaldehyde; furfural; furfuryl alcohol; 5-methylfurfural; 2-octanol; phenol; Guaiacol; m- and p-methoxyphenol; o-, m-, and p-cresols; Veratrole; isobutyric acid; butyric acid; naphthalene; Estragole; Anethole; Eugenol; 2-methoxy-4-ethylphenol; 2-methoxy-4-propylphenol; Isoeugenol; dimethylphenols; hydroquinone; 2-hydroxy-5-methoxybenzaldehyde; and 2-hydroxyacetophenone. Included among the chemical processes occurring over a period of time in the pyrolytic oils are the formation of acetals through the reaction of aldehydes and alcohols. Under the low p^H conditions of the pyrolytic oils, Isoeugenol polymerizes readily. Other components which might polymerize under the conditions include Eugenol, Anethole, and Estragole. A fresh sample of pyrolytic oil was hydrogenated in an attempt to stabilize the oil against polymerization. Hydrogenation of the oil resulted principally in the conversion of Isoeugenol and Eugenol to 2-methoxy-4-propylphenol. A phenol fraction was extracted from the pyrolytic oil samples and reacted with formaldehyde to obtain a phenol-formaldehyde resin.

INTRODUCTION

Every year large amounts of agricultural waste are produced in the United States. The disposal of this waste material is becoming an increasingly more difficult and expensive matter. Also there is a critical need for new energy sources in the United States. Agricultural wastes are largely lignocellulosic in chemical nature. Pyrolysis is an excellent approach for the conversion of agricultural and wood manufacturing wastes to useful energy or chemical forms.

Pyrolysis of solid agricultural waste yields a noncondensable gas, a liquid, and a solid carbonaceous char.[1] Analysis of the evolved pyrolytic gas stream indicates the presence of hydrogen, carbon dioxide, carbon monoxide, methane, ethane, and ethylene. The individual gas compositions vary with pyrolysis conditions. The solid material which remains after pyrolysis is an impure carbon and ash. The liquid fraction or pyrolytic oil contains organics and water.

Workers at the Engineering Experiment Station at the Georgia Institute of Technology have shown that pyrolysis is readily utilized for the conversion of cellulosic and lignocellulosic wastes into useful fuels and other products. A large prototype pilot pyrolysis system constructed in 1972[2] was built to operate continuously at an input feed rate of 300 to 500 lbs. of waste per hour. The system includes a waste receiving bin, a belt conveyer to the converter, the converter and char handling system, an off-gas cyclone, a condenser and a gas burner. Peanut shells, wood chips, pine bark and sawdust, municipal wastes, macadamia nut hulls and cotton gin wastes have been pyrolyzed in the pilot plant. A large 50 ton/day demonstration plant which is owned and operated by the Tech-Air Corporation is located in a wood yard in Cordele, Georgia and is operated on wastes from the sawmill.

The pyrolytic oils are mixtures of neutral compounds and strong and weak acids with pH's of 3-4. The oils are viscous, sticky liquids at room temperature. The pyrolytic oils appear to oxidize and/or polymerize on standing and in the process undergo an increase in viscosity.

Many investigators have determined the products of the pyrolysis and distillation of wood. Some of the products identified are: aphthalene; dimethylnaphthalene; 2,3-dimethylanthracene; 2-methoxy-4-methylphenol; Guaiacol; 2-methoxy-4-ethylphenol; 2-methoxy-4-propylphenol; phenol; cresols; xylenols; pyrocatechol; 4-methylpyrocatechol; dimethylpyrogallol; 4-hydroxy-3-methoxytoluene; 4-hydroxy-3-methoxystyrene Eugenol; cis-Isoeugenol; trans-Isoeugenol; Vanillin; acetovanillone; pyrogallol 1,3-dimethylether; 4-hydroxy-3,5-dimethoxytoluene, 4-hydroxystyrene; 4-hydroxy-3-methoxystyrene; 4-hydroxy-3-methoxy-1-vinylbenzene; 4-hydroxy-3,5-dimethoxy-1-ethylbenzene; benzene; sinasaldehyde; coniferaldehyde; syringaldehyde; allylsyringol; methylnaphthalene; p-ethylphenol; 2,4,6-trimethylphenol; α-naphthol; p-hydroxybenzaldehyde; p-hydroxyacetophenone; acetosyringone; butyrolactone; crotonic acid; maltol; 2-hydroxy-3-methyl-Δ2-cyclopentenone; 2,6-dimethoxyphenol; tiglaldehyde; methyl isopropyl ketone; methyl ethyl ketone; methyl furyl ketone; acetaldehyde; furan; 2,3-butandione; methylfuran; 1-hydroxy-2-propanone; glyoxal; acetic acid; furfural; acetone; propionaldehyde; methanol; 3-hydroxy-2-butanone; ethanol; diacetyl; furfuryl alcohol; formaldehyde; 1-butanol; isobutyl alcohol; anthracene; and phenanthrene.[3-14]

Our objectives were to develop methods for determining the chemical composition of the pyrolytic oils immediately after collection and then to observe any changes in the chemical composition of the oils as a function of increasing viscosity. Also, after the mechanism of the increase in viscosity of the pyrolytic oils had been determined, attempts were to be made to stabilize the pyrolytic oils against whatever changes they undergo. We also proposed to evaluate pyrolytic oils as a feedstock for the recovery and production of chemicals and to routinely analyze pyrolytic oil samples submitted by the pyrolytic oil research group at the Engineering Experiment Station at the Georgia Institute of Technology.

ANALYTICAL STUDIES

GC/MS of Condenser Oil Distillate

Qualitative analysis of the condenser oil distillate by combined gas chromatography-mass spectrometry was performed on a DuPont Model 21-490 GC-Mass Spectrometer. The major components identified were: ethanol; 1-butanol; isobutanol; acetaldehyde; furfural; furfuryl alcohol, 5-methylfurfural; 2-octanol; phenol; Guaiacol; m- and p-methoxyphenol; o-, m- and p-cresols; Veratrole; isobutyric acid; butyric acid; naphthalene; Estragole; Anethole; Eugenol; 2-methoxy-4- propylphenol; Isoeugenol; dimethylphenols; hydroquinone; 2-hydroxy-5-methoxybenzaldehyde; and 2-hydroxyacetophenone.

Composition of Distillate as a Function of Time

Over a period of six months, the alcohol, aldehyde, and acid peaks decreased substantially in area. The decreases in area are due to the formation of esters and acetals under acidic conditions over a period of time. These conclusions are in agreement with the observation of Knight that there was an increase in water content for a pyrolytic oil sample stored over a period of eight months.[15]

The peak which contained Estragole (4-allylanisole) also decreased substantially in area over that same period. That bit of experimental data caused us to investigate the facility of cationic chain-reaction polymerization of other olefins in the oils which might potentially undergo polymerization. Anethole, Estragole, Eugenol, and Isoeugenol were separately added to 3MHCl solutions. Isoeugenol formed a solid precipitate overnight. Eugenol formed a brown, viscous gel. Anethole and Estragole formed brown oils.

Capillary Gas Chromatography

The condenser oil filtrate (acetone) and condenser oil distillate were analyzed on a Varian 3740 capillary gas chromatograph with a flame ionization detector. The chromatograms are shown in Figures 1A and 1B. The conditions were: a 30 meter Supelco 2-3700 glass capillary grade AA SP 2100 column (internal diameter ca. 0.25 mm), and an oven temperature program of 40°C-220°C at 5°C per min. The He flow rate was 1.0 ml/min. The chromatograms were obtained in the direct injection mode. Peak identifications were made by noting the enhancement of peak size when known substances were added to the samples. Peak assignments and quantitative data are presented in Tables 1 and 2.

EXTRACTION OF PHENOLS FROM PYROLYTIC OILS

Phenols may be removed from the pyrolytic oil by (1) extracting with water and discarding the aqueous layer, (2) extracting with 1.0N $NaHCO_3$ to remove the carboxylic acids and (3) extracting with 2.5N NaOH followed by neutralization with 5% HCl solution. The capillary gas chromatogram of the phenol extract is shown in Figure 2. The peaks at retention times of 16.4 (7.0gc %), 17.9 (5.7gc %), 18.0 (3.3gc %), 19.0 (10.0gc %), 21.0 (14.0gc %), 24.7 (4.0gc %), and 28.4 (3.9gc %) minutes are phenol, Guaiacol, o-cresol, m-and p-cresol, 2-methoxy-4-methylphenol, Eugenol and Isoeugenol, respectively.

PREPARATION OF PHENOL-FORMALDEHYDE RESINS

Other investigators have used the tar[16] and creosote[17] fractions from wood pyrolysis for the preparation of phenol-formaldehyde resins. The phenol extracts (35g) were condensed with 42g of formalin in aqueous barium hydroxide solution. A low molecular weight reosole (7.9g) was formed which after additional heating formed a crosslinked resin.

EVALUATION OF PYROLYTIC OILS AS A FEEDSTOCK FOR THE RECOVERY OF CHEMICALS

The potential of the pyrolytic oils as a source of chemicals is excellent. The valuable chemicals present in the pyrolytic oils and their prices are shown as listed in the August 21, 1978 issue of CHEMICAL MARKETING REPORTER.[18]

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the U.S. Environmental Protection Agency, Municipal Environmental Research Laboratory, Cincinnati, Ohio for support of this work under Grant No. R-804440020.

REFERENCES

1. "Pyrolysis of Solid Municipal Wastes," E.P.A. Report No. 670/273-039.
2. Knight, J.A., Tatom, J.W., Bower, M.D., Colcord, A.R., and Elston, L.W. "Pyrolytic Conversion of Agricultural Wastes to Fuels," 1974 Annual Meeting of the American Society of Agricultural Engineers.
3. Shafizadeh, F., Sarkanen, K.V., and Tillman, D.A., "Thermal Uses and Properties of Carbohydrates and Lignins," Academic Press, New York (1976).
4. Reznikow, V.M. and Novskii, Khim. Prir. Soedin, 11 (1), 77-83 (1975). CA. 83:44948h.
5. Vodqinskaya, A.R. and Tischenko, D.V., Gidroliz i Lesokhim Prom, 10, No. 5, 9-11 (1957). CA. 51:18604.
6. Shaposhnikov, Y.Z., Kosyukova, L.V., and Volkova, E.P., Gidroliz Lesokhim. Prom. 20 (1), 16-17 (1967). CA. 66:77124.
7. Kitoa, K. and Watanabe, Y., Zairyo, 16 (169) 844, (1967). CA. 68:88238.
8. Yasumity, W. and Koichiro, K., Mokyzai Kenkyu 38 (7), 40 (1958).
9. Gavars, M., Domburgs, G., Liepins, M., Tikhomirov, M., Khim. Ispol'z Lignina, 368-75 (1974).
10. Chuprova, N.A. and Levin, E.D., Khim. Tekhrol. Polim., No. 3, 78-83 (1972).
11. Levin, E.c., Tikhomirov, G.V., and Popva, N.A., Materialy Konf. po. Itogam. Nauchn. Issled. Rabotza 1964 god, Sibirsk Tekhnol. Inst. Krasnovarsk, USSR, 54-7 (1965). CA. 65:5659.
12. Hartley, R.D., J. Chromatogr. 54 (3), 335-44 (1971). CA. 74:83835.
13. Goos, A.W. and Reites, A.A., Ind. Eng. Chem. 38, 132-35 (1946).

14. Hawley, L.F. and Wise, L.E., "The Chemistry of Wood," The Chemical Catalog Co., Inc., New York (1926).

15. Knight, J.A., Personal Communication.

16. Smolanka, I.V., Dokl. i Soobshch. Uzhgorodsk. Gos. Univ. Ser. Khim., No. 4, 3508 (1961).

17. Slavyanskii, A.K. and Piyalkin, V.N., Izv. Vysschkh Uchebn. Zabedenii Lesn. Zh., 5, No. 2, 124-6 (1962).

18. Chemical Marketing Reporter, p. 49-59, August 21, 1978, Schnell Publishing Company, Inc., New York.

TABLE 1. Condenser Oil Filtrate Capillary Gas Chromatogram Results

Peak No.	Retention Time (Min)	GC %	Assignment
3	5.6	0.76	Isobutyl Alcohol
4	5.8	1.95	1-Butanol
13	9.2	1.81	Furfural
17	11.5	1.45	Furfuryl Alcohol
21	13.0	0.62	5-Methylfurfural
30	15.3	2.18	2-Octanol
34	16.4	4.63	Phenol
37	17.7	5.15	Guaiacol
38	18.0	1.02	o-Cresol
42	18.9	7.90	m-and p-Cresol
48	20.5	1.24	Naphthalene
50	20.9	12.98	2-Methoxy-4-methylphenol
51	21.4	1.29	Dimethylphenol
58	23.4	2.19	2-Methoxy-4-ethylphenol
64	24.7	2.82	2-Hydroxy-4-methoxybenzaldehyde
66	25.1	2.08	Unknown
69	25.7	1.69	Eugenol
70	25.9	1.17	2-Methoxy-4-propylphenol
79	28.4	8.91	Isoeugenol

TABLE 2. Condenser Oil Distillate Peak Enhancement Results from Capillary Column

Peak No.	Retention Time (Min)	GC %	Assignment
13	9.2	0.27	Furfural
17	11.5	0.71	Furfuryl Alcohol
21	12.8	0.36	5-Methylfurfural
30	15.3	0.76	2-Octanol
34	16.4	5.67	Phenol
37	17.7	4.71	Guaiacol
38	17.9	2.50	o-Cresol
42	18.8	5.97	m-and p-Cresol
48	20.5	2.72	Naphthalene
50	20.9	10.40	2-Methoxy-4-methyphenol
51	21.4	3.00	Dimethylphenol
58	23.4	4.83	2-Methoxy-4-ethylphenol
69	25.6	2.20	Eugenol
70	25.9	1.69	2-Methoxy-4-propylphenol
79	28.3	3.08	Isoeugenol

TABLE 3. Current Prices of Chemicals Present in the Pyrolytic Oils

Chemical	Price $ per lb.	Comments
Acetaldehyde	0.20	99%
Acetic Acid	0.18	technical grade
Acetone	0.17	
n-Butyl Alcohol	0.21	fermentation grade
sec-Butyl Alcohol	0.23	synthetic
Butyric Acid	0.325	
m-Cresol	0.98	95-98%
m,p-Cresol	0.44	90%
o-Cresol	0.50	30.5°C m.p.
Ethyl Alcohol	1.12	190 proof
Eugenol	4.25	USP
Furfural	0.515	
Furfuryl Alcohol	0.54	
Guaiacol	2.60	technical grade
Hexyl Alcohol	0.24	mixed isomers
Hydroquinone	1.54	technical grade
Isobutyl Alcohol	0.19	
Isoeugenol	6.85	
Methanol	0.44	synthetic

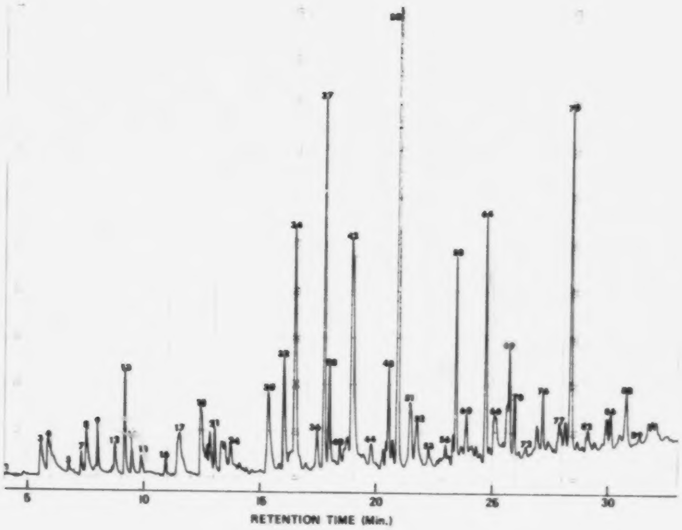


Figure 1A. Capillary Gas Chromatogram of Pine Condenser Oil After Filtration in Acetone.

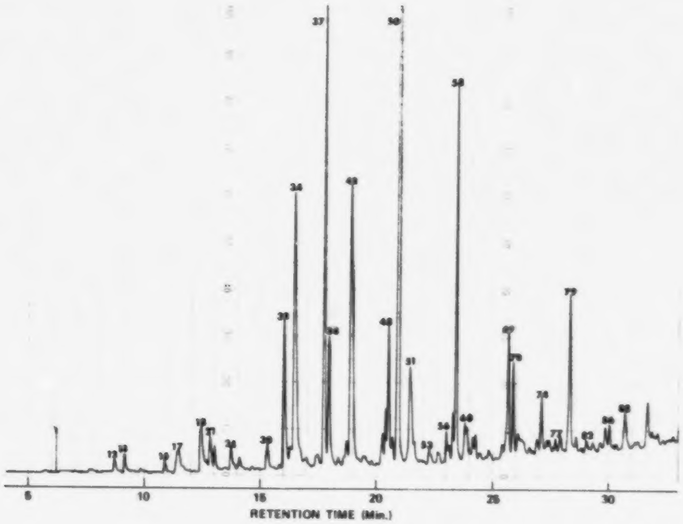


Figure 1B. Capillary Gas Chromatogram of Pine Condenser Oil Distillate.

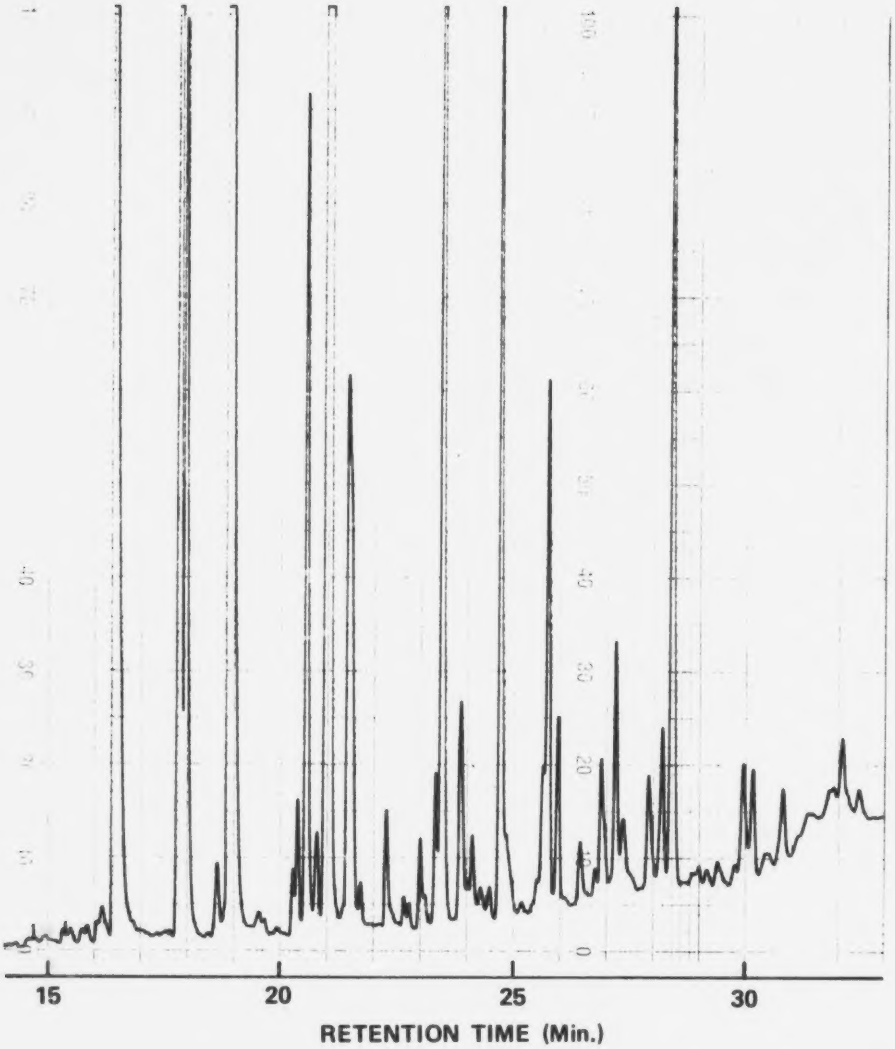


Figure 2. Capillary Gas Chromatogram of Phenolic Extract.

PYROLYTIC OILS FROM AGRICULTURAL AND FORESTRY RESIDUES AND MUNICIPAL SOLID WASTE

J. A. Knight
Engineering Experiment Station
Georgia Institute of Technology
Atlanta, Georgia 30332

ABSTRACT

Pyrolytic oils can be produced in varying yields (15 to 25%) by the pyrolysis of agricultural and forestry residues and municipal solid waste. Charcoal and combustible gases are produced at the same time. Georgia Tech has developed a pyrolysis process, which has been successfully demonstrated in a field demonstration facility at better than 90% on-time of rated capacity. The quantities of biomass residues and cull and salvable dead trees in the United States provide a tremendous resource for the potential production of large quantities of pyrolytic oil along with the charcoal and combustible gases. The oils contain a wide spectrum of organic compounds from low-boiling to high boiling, and many of the compounds are oxygenated. The two major potential applications of the oils are as a fuel and as a source of chemical materials for industrial applications. The utility of the oils as a fuel has been demonstrated. In order for the oil to be used as a source of chemicals, processing techniques must be developed for separating the oil into fractions of the major chemical species present in the oils.

INTRODUCTION

Large quantities of agricultural, forestry and municipal wastes are produced each year in the United States. The proper utilization of these materials so that they can be considered a resource rather than wastes is of extreme importance to the country. At the same time, the disposal and environmental problems these wastes create would be solved. One approach for the utilization of these materials that has received a great deal of attention in the past few years is pyrolysis. Pyrolysis of lignocellulosic and/or cellulosic material produces char, pyrolytic oil, water containing water-soluble organic substances, and non-condensible gases. The char is primarily carbon and can be used as a fuel or converted to activated carbon, to produce gas for use as a clean burning gaseous fuel or to synthesize gas for organic synthesis. The major components of the non-condensible gases are hydrogen, carbon monoxide, carbon dioxide and methane along with minor amounts of the other hydro-carbon gases. The gas can be utilized on-site as a clean burning low BTU gaseous fuel. The pyrolytic oils are clean burning with heating values approximately sixty percent the heating values of fuel oils. There is, however, a great potential for utilizing pyrolytic oils as a source of chemical materials for industrial applications and/or as a chemical feedstock. By upgrading the oils for uses of greater value than as a fuel the total economic benefit from waste materials would be of greater significance to the country. Also, the utilization of oils produced from current waste materials as a source of chemical materials would reduce the demand on petroleum materials for chemical feedstock.

Pyrolytic oils are complex mixtures of organic compounds ranging from very volatile to high boiling materials. Many of the compounds are oxygenated, and the oils therefore are quite different in their chemical and physical properties from petroleum. The characterization of these oils and fractions obtained from them to determine physical and chemical properties provides the necessary data for the development of the technology to process the oils into more useful chemical materials for industrial chemical applications.

GEORGIA TECH VERTICAL-BED PYROLYSIS SYSTEM

Over the past ten years, a vertical-bed pyrolysis system has been developed at the Georgia Institute of Technology. Lowen et. al., have recently described in detail this development and process [1]. The Tech-Air Corporation licensed the process for commercialization in 1970, and in 1975, the American Can Company acquired Tech-Air as a wholly-owned subsidiary.

The Georgia Tech pyrolysis process has been demonstrated very successfully by the Tech-Air facility at Cordele, Georgia. For several months in the latter part of 1977 and into mid-1978, Tech-Air operated their field demonstration facility (40 dry tons/day) at better than 90 percent on-time of rated capacity. The Georgia Tech pyrolysis system can be operated to provide a variable yield of a given product (i.e., char) with a corresponding variation in the yields of the other products (i.e., gas and oil). The char yields can be varied from about 10 percent to 35 percent. The pyrolytic oil yield can be varied from about 15 percent to 25 percent. The gross energy recovery in the form of products -- char, oil and gas -- is approximately 95 percent of the energy in the dry feed.

POTENTIAL QUANTITIES OF PYROLYTIC OILS

The quantities of biomass residues in the U.S. are a potential source of significant amounts of chemical materials. The yield of pyrolytic oil from lignocellulosic materials will vary from 15 to 25 percent depending upon the feed material and the conditions of pyrolysis.

Accurate estimates of waste materials generated in the U.S. are difficult to obtain. Tillman [2] has recently reported that 80 million oven dry tons of wood residues from processing and manufacturing operations are available annually in the United States. This quantity of material has the potential for providing 12 to 20 million tons of pyrolytic oil which is about 24 to 40 percent of the tonnage of petroleum used by the chemical industry as chemical feedstock. In addition to the available wood residues, there is a potential source of approximately one billion dry tons of cull or rough trees and salvable dead trees in the United States [2]. The importance and significance of these large quantities are that utilization of waste materials and noncommercial timber, which are unused resources, could have a tremendous impact as a source of chemical materials as well as providing clean burning fuels. In addition the utilization of these unused resources would benefit the environment and reduce dependence on imports of foreign oil.

ANALYSIS AND TESTING OF PYROLYTIC OILS

The analysis of pyrolytic oils for physical and chemical properties and characteristics can be done by many of the analytical procedures and techniques that are utilized for petroleum, vegetable and other oils. Knight et. al., have reported on the physical and chemical characterization of pyrolytic oils produced by the Georgia Tech pyrolysis process from a pine bark-sawdust mixture [3]. Typical properties that are determined for pyrolytic oils are density, water content, heating value, acidity, flash point, pour point, filterable solids, ash, corrosiveness, viscosity, and elemental content. The water content of oils produced by the pyrolysis of agricultural and forestry wastes is particularly significant. The amount of water in pyrolytic oils is determined by the conditions of the recovery of the condensible organic phase from the off-gas stream from the pyrolysis reactor. The water contained in pyrolytic oils is well-emulsified and does not separate on standing. In general, the operating conditions for the recovery of oil from the off-gas stream of the Georgia Tech system produce oils with a water content in the 10 to 15 percent range.

The chemical characteristics of the oil are of significance in the evaluation of the oils for chemical applications. Analytical methods and techniques that are useful for determining the chemical nature of the oils are gas and liquid chromotography, gas chromotography/mass spectroscopy, and infrared and ultraviolet spectroscopy.

PROPERTIES AND CHARACTERISTICS OF PYROLYTIC OILS

Oils produced by the pyrolysis of lignocellulosic materials are complex chemical materials with a wide spectrum of organic compounds. The oils are reddish brown to black; have a burnt, pungent odor; are acidic and slightly corrosive; have heating values about sixty percent the heating values of fuel oils; have a density greater than water; and are heat sensitive. Some properties of pyrolytic oils produced from a pine bark-sawdust mixture by the Georgia Tech process are given in Table 1.

TABLE 1. PROPERTIES OF PYROLYTIC OILS

Property	Value
Density	9.2 - 9.5 lbs/gal
Heating Value	9,000 - 11,500 Btu/lb
pH	∿ 3.0
Acid Number	30 - 75 mg KOH/g
Flash Point	111° - 121°C
Pour Point	27°C
Filterable Solids	0.3 - 0.4%
Ash	< 0.1%
Water Content	10 - 15%

The viscosity of pyrolytic oils depends upon the operating conditions for pyrolysis and the amount of water condensed with the oil. The water is well emulsified in the oil. The Georgia Tech process is generally operated so that the water content of the oils is in the 10-15 percent range. These oils are relatively free flowing, but oils which are essentially free of water are viscous, and some have a grease-like consistency at ambient temperature. The oils are heat sensitive and prolonged heating will result in increasing viscosity with eventual formation of solids. A number of viscosity-temperature curves have been reported [3].

The oils have been distilled at both atmospheric and reduced pressure [3]. Due to the heat sensitivity of the oils, only 55 to 65 percent of the oils can be distilled. As the distillation proceeds, the oil in the distilling flask becomes more viscous, and in the range of 180° to 200°C, the material in the flask will begin to smoke with continued heating. Prolonged heating results in decomposition of the material in the flask. Fractional distillation of vacuum distilled pyrolytic oil did not yield any fractions of close boiling range. The liquid chromatograms of the fractions indicated, however, that the more polar and water soluble components were concentrated in the low boiling fractions whereas the less polar components were concentrated in the high boiling fractions.

Hydrogenation of the oil at 4 and 20 atmospheres with a Pd catalyst showed that about 2 mg of hydrogen per gram of oil was absorbed. If one assumes an average molecular weight of 150 for the oil, then approximately 0.15 mole of hydrogen is absorbed per mole of oil.

The pyrolytic oils contain a wide spectrum of organic compounds from low boiling to high boiling. Many of the compounds are oxygenated, and consequently, a variety of functional groups are present in the oils. These functional groups contribute to the chemical properties and reactivity of the oils. The major classes of organic chemical species found in the pyrolytic oils produced from forestry materials by the Georgia Tech process are: phenolics, approximately 17-22%; aromatic neutral compounds, approximately, 34-42%; acids, approximately 6-7%, and "sugar-type" substances, approximately 20-24%.

POTENTIAL APPLICATIONS OF PYROLYTIC OILS

The pyrolytic oils produced from agricultural and forestry residues and municipal refuse have potential applications as a fuel and as a source of chemical materials for industrial applications.

The heating values of pyrolytic oils with 10 to 15 percent water are 60 to 70 percent of the heating values of fuel oils on a volume basis. The water in pyrolytic oils reduces the heating value on a mass basis, but it also reduces the viscosity of the oils, which aids in the material handling of the oils and probably aids in the atomizing of the oil. The pyrolytic oil produced by Tech-Air at its field demonstration facility in Cordele, Georgia, was sold as a fuel [1]. The oil was sold for use as a fuel in a cement kiln, a power boiler and a lime kiln. Pyrolytic oils have potential use as a fuel for a hot gas turbine. The utilization of the pyrolytic oils as a fuel has been demonstrated. With satisfactory combustion conditions the oil can be burned cleanly. Since it has essentially zero sulfur, SO_x emissions are not a problem. It can be admixed with sulfur-containing fuel oil to reduce the SO_x emissions to acceptable levels. In the handling and storage of the oil, it is necessary to take into account the slight corrosive nature of the oils and the effect of prolonged, relatively high temperatures on the oils.

The Pittsburgh Energy Research Center test fired a slurry of number six fuel oil and a 60-40 mixture of low volatile wood charcoal and pyrolytic oil. The slurry was prepared to contain 30 percent wood charcoal [4]. The slurry was fired in a 100 HP oil fired, packaged firetube boiler. The flame stability in all tests was reported as excellent. The NO_x emissions were lower than those obtained from firing a coal-oil slurry, and the SO_x emissions were proportionate to the concentration of sulfur in the slurry. The results of these combustion tests demonstrate that the charcoal and pyrolytic oil can be fired successfully and are ideal fuels to mix with coal and petroleum fuel oils to reduce SO_x emissions and to conserve diminishing petroleum reserves.

The potential utilization of pyrolytic oils as a source of chemical materials for industrial applications depends upon the development of processing techniques which will separate the oils into fractions of the major chemical species found in the oils. Research and development work is currently in progress at Georgia Tech to develop separation processes for pyrolytic oils. The phenolic fractions should find immediate application in the production of phenolic-formaldehyde resins for the plywood and particle-board industries. The aromatic neutral fractions should have potential applications in many diverse fields such as the rubber, plastics and asphalt industries. Well characterized fractions from crude pyrolytic oils will, no doubt, suggest many industrial applications for these chemical materials.

REFERENCES

1. Bowen, M. D., Smyly, E. D., Knight, J. A., and Purdy, K. R. A Vertical-Bed Pyrolysis System, pp. 94-125, ACS Symposium Series, No. 76, Solid Wastes and Residues, Jones, J. L. and Radding, S. B., editors (1978).

2. Tillman, D. A. Wood as an Energy Source. Academic Press, Inc., New York (1978).

3. Knight, J. A., Hurst, D. R., and Elston, L. W. Wood Oil from Pyrolysis of Pine Bark-Sawdust Mixture, pp. 169-195. Fuels and Energy From Renewable Resources, Tillman, D. A., Sarkanen, K. V. and Anderson, L. L., editors, Academic Press, Inc., New York (1977).

4. Demeter, J. J., McCann, C. R., Ekmann, J. M. and Bierstock, D. Combustion of Char From Pyrolyzed Wood Waste, Pittsburgh Energy Research Center, PERC/RI-77/9 (1977).

This work was supported in part by grant R804410 from the Municipal Environmental Research Laboratory, U. S. EPA, Cincinnati, Ohio.

SOME EMPIRICAL EVIDENCE ON THE EFFECTS OF USER CHARGES FOR SOLID WASTE COLLECTION SERVICES

Robert J. Anderson, Jr.(1)
Vice President, MATHTECH, Inc.
P. O. Box 2392
Princeton, New Jersey 08540

ABSTRACT

A basic proposition of economics is that when the prices of goods and services increase, other things being equal, the quantity demanded of them will decrease. Economists have suggested that this relationship between price and demand could be used by solid waste managers as a tool for encouraging household waste reduction. Waste reduction would be accomplished by levying charges for solid waste collection and disposal.

This paper presents empirical evidence from Tacoma, Washington, on the sensitivity of demand for solid waste collection and disposal services to price. It suggests that (a) households' choices of a service for waste collection and disposal may be sensitive to price, and (b) that the total quantity of waste generated may not be very sensitive to price.

INTRODUCTION

Economists have long argued that solid waste collection and disposal should be financed through fees levied on households, businesses, and governments, with fee levels set equal to the costs of the solid waste services provided to them. The rationale for this position is as follows: If solid waste services are provided free of charge, waste generators are encouraged to use too many solid waste collection services. If, in contrast, services are priced at the cost of producing them, service users will balance their willingness-to-pay for services with the costs of production of those services. In general, the higher the charge for the service, the less it will be used.

Inspite of the near-universal acceptance by economists of the proposition that service demands and service price levels are inversely related, there is almost no empirical analysis available to support it. One study, a cross section study by Stevens(2), provides some evidence that service demand declines if service price is increased, other things being equal. In particular, Stevens finds that the percentage of households subscribing to backyard service in communities offering this option is about .26 percent lower for each one percent positive difference in the charge for backyard service. She also finds that a one percent positive difference in the charge for more frequent collection leads to approximately a 0.90 percent negative difference in the percentage of households choosing twice weekly collection, and approximately a .05 percent negative difference in tonnage of refuse collected.

This paper examines some time series evidence from a single municipality -- Tacoma, Washington -- employing a user charge. My analysis will show statistically significant negative relationships between the number of households choosing a particular service level and the level of the charge for the corresponding service. Estimated service price elasticities vary from substantially less than one for low levels of service usage to substantially in excess of one for high service levels. These results also will show relatively little relationship between service prices and total quantities of waste generated. Taken together, these results imply that pricing policy may have a relatively large effect on households' choices of services for disposing of solid waste, but a relatively small effect on how much waste they generate.

The plan of the paper is as follows: In the next section, the solid waste collection system and charge policy employed in Tacoma are briefly reviewed. Tacoma offers a large number of service levels, distinguished by the number of containers picked up, the distance from curbside at which the containers are placed for collection, and the number of flights of stairs above curb level at which containers are presented for collection.

The section entitled "Model and Results" describes the statistical models I have employed to characterize the demand for collection services in Tacoma. These models include a multinomial logit model of qualitative choice to explain choice among alternative services, and a regression model to explain total quantity generated and its disposition between collection, self-hauling, and littering.

As noted above, the results presented above suggest substantial sensitivity of service usage to price at high levels of usage (i.e., more than one can and/or at some distance from the curb). Indeed, for all but the basic level of service (one can at curb-side), my estimates imply elasticities considerably in excess of one. If correct, this means that individual households' demands for service at high levels of service usage may be somewhat more elastic than is reflected in the empirical results of Stevens.

My results on the effect of price on total quantity of household waste generated suggest that the effect on total waste generation in Tacoma is nearly zero. In particular, the estimates do show some weak (statistically significant at the 10 percent level) evidence that quantities presented for collection decrease, and quantities self-hauled increase in an offsetting amount. These two effects roughly cancel, with the result that total waste generation appears to remain roughly constant, other things being equal.

I conclude with a discussion of some possible implications of my findings. The most obvious implication is that cost-based service pricing may result in a substantial reduction in the demand for solid waste collection services. This in turn means that the economic efficiency of collection could be improved substantially by a charge policy.

USER CHARGES AND SOLID WASTE COLLECTION AND DISPOSAL IN TACOMA, WASHINGTON

Collection and Disposal

Tacoma's solid waste disposal system serves a total population of about 177,000 -- 157,000 city residents and 20,000 outside the city who either haul their own refuse to the landfill or receive collection services from haulers who utilize the Tacoma landfill. About 3.5 percent of refuse processed at the city landfill originates outside Tacoma; figures are unavailable on how much waste originating in Tacoma is disposed outside the city, but the amount is probably negligible. The city collects 56 percent of Tacoma's solid waste, and another 15 percent is hauled by residents to the landfill. Since 40 percent of the city's collection is from residential sources, household solid waste accounts for 37 percent of the total generated in the city (i.e., 15 percent + 40 percent x 56 percent = 37 percent), or about 1.2 tons/household annually. The user fee charged to Tacoma residents for household collection includes a charge for disposal of $6.17 per ton. Commercial haulers are charged at $6.17 per ton for refuse originating in Tacoma, with a $3 minimum charge and a $1.25/hour dumping fee for each hour per load over one hour. Commerical haulers are charged $9.92 per ton for refuse originating outside Tacoma, with a $5 minimum, and private residents from outside Tacoma are charged $3.15 for refuse brought to the landfill in cars and $5 for refuse brought in pickups. Tacoma residents are allowed to bring household refuse to the landfill in cars or pickups free of charge.

Tacoma operates a fleet of 24 collection trucks, 22 of which serve residential routes. Refuse is collected once a week from each residential customer, and crews work a five-day week. Trucks are operated by two-man crews sharing driver and collector responsibilities. The driver carries a route book listing name, address, and current service level of each customer, and in which a record of extra bags collected and changes in services are kept. Three route supervisors handle most customer requests such as requests for extra collections or service changes, and reports of unsanitary conditions. The route supervisor posts were created between 1973 and 1975 at the same time as the collection crew size was reduced from three to two. The change in staff structure is felt to have resulted in reductions in paperwork, more efficient routing, and improvements in safety, equipment operation, and customer relations and service. Employees of the Refuse Utility have been organized in the Teamsters Union since the 1940's; labor relations have been good in recent years.

The last major restructuring of refuse collection took place in 1929 when the Refuse Utility was inaugurated. Refuse had previously been collected by private haulers on a purely voluntary basis. Of some 24,000 households in Tacoma in 1929, only 6,000 subscribed to collection services. The majority disposed of their own refuse in a satisfactory manner. A serious health hazard was not created from garbage left in streets, on vacant lots, and alongroads on the edge of the city. One of the first first actions of the new utility was a massive clean-up campaign. A dump site was created in the swamp on the eastern edge of the city which was used for over thirty years. This land was eventually utilized for industrial development over former tidal flats.

Today Tacoma's landfill is still inside city limits, less than 13 kilometers from any point in the city. Hauling costs for both the city and for private residents taking refuse to the landfill are considerably less than they might be if the landfills were outside the city, so a great deal of effort has been devoted to prolonging use of the present site. The original landfill in former swampland on the eastern edge of the city reached capacity in 1960, when the present landfill, a ravine southwest of the city center, was acquired. The 81 hectare site of the ravine was originally expected to serve Tacoma's disposal requirements for 10 years, but cost estimates in the mid-sixties indicated that to prolong the life of the landfill would result in considerable savings since no more suitable sites were available in or near the city. Consequently, several projects have been undertaken with the aim of resource recovery and reduction of the volume of waste disposed.

User Charges

Tacoma has some 50 years' experience in financing solid waste collection and disposal through user fees. The present fee structure is a combination of a capacity-based system and a location- or service-based system.

Residential households living in single unit or duplex structures receive mandatory weekly collection at a rate determined by the number of containers presented for collection and the level of carryout service provided. Households presenting refuse within 7.6 meters of a legal collection point (usually curbside, but alleys in some districts) are charged $2.45 per month for the first can and $1.15 per month for each additional can. Those presenting refuse between 7.6 and 22.9 meters from collection points are charged $3.90 for the first can and $2.65 for each subsequent can. Between 22.9 and 61.0 meters, and over 61 meters, the base prices are $5.30 and $6.65 and marginal prices are $4.05 and $5.45, respectively. A charge of $1.60 times the number of cans is levied for each flight of up to six stairs between points of collection and presentation. These are monthly fees paid along with electricity, water, and sewage bills on a monthly of bi-monthly basis. In addition, occasional extra bags of refuse left alongside regular cans are collected for a charge of $.75 each.

The original fee structure introduced in 1929 varied only according to pickup location; this was at a time when almost all households probably demanded one can per week or less. Since the introduction of a variable fee for quantity collected in 1938, the marginal rate for added quantity has steadily decreased as a proportion of the basic rate for minimum service, while the marginal rate for added location-based service has increased relative to the basic rate.

The "bag" system, whereby residents would be required to place rubbish in bags whose price includes the cost of collection and disposal, was established in 1976. It was estimated in 1974 that $50,000 to $100,000 in revenue were lost annually by not charging for bags left for collection by households who had extra refuse occasionally, but not often enough to warrant purchasing an additional can of weekly service. In April 1974 the Utilities Service Director put forward a plan to sell plastic bags through the city's fire stations for 50 cents each to be used for these "occasional extras." Consideration was also given to making a complete changeover to the bag system for all household refuse collection. This latter plan was rejected for several reasons: it would require changing the city's ordinances regarding the storage of refuse in rodent-proof containers; it was felt that plastic bags were too expensive (13 to 14 cents each); and paper bags would deteriorate in the damp climate. Because of problems with arranging for distribution of bags, the more limited bag system for extras only was rejected. Also, shops and supermarkets were generally unenthusiastic about serving as retail outlets, and fire stations were not always sufficiently staffed.

An alternate to the bag system was finally adopted in May 1976. Collection crews are given special cards on which to note the address and number of bags for any extra pickups. A clerk records this information along with the account number of the address where the extras were left, and the customer is billed at the end of the month. The price of this service is set at a level that makes it cheaper for households to use an extra can all the time if they have an extra bag of refuse at least twice a month on average. During the first year this system was estimated to have cost about $17,000 while developing added revenues of about $69,000.

Administration of the System

Tacoma's solid waste system is constituted as a classified utility under the Department of Public Works. This is an intermediate form between a department of local government and an independent public utility. Like most public utilities, the solid waste system must finance its operations (including capital expenditures, debt service, and taxes) out of revenue it collects rather than from general funds, and its staff, equipment, and land are autonomous from local government. But unlike many utilities, its governing board is the city council rather than a separate utilities commission.

Tacoma's experience in finding a way to collect user fees for extra bags of refuse illustrates some of the administrative advantages of a combination of capacity -- and location -- based systems. Because the fee structure has several parts (varying according to number of containers, distance from collection point, etc.) it has been possible to adjust the relative prices of these items as costs have changed. In turn, this has meant that economic constraints have been available in place of legal constraints such as limits on quantities or pickup location. One of the alleged benefits of the bag system is the elimination of administrative costs associated with recording service levels and billing each household separately. But in order to realize fully this benefit Tacoma would have to eliminate entirely location-based variables from its fee structure, since these require separate records and billing in any case. For Tacoma, the card system involved few additional administrative costs while still yielding most of the benefits of the bag system. In general, once a particular fee structure is adopted it may be costly to modify service or price. A combination fee structure is flexible in allowing piecemeal changes in one of several areas independently, provided that all such changes are compatible with all parts of the current system.

Judging from press reports, records of council debate, and numbers of complaints, the Tacoma Refuse Utility has caused little public dissatisfaction or political controversy in recent years. The price of collection and disposal in Tacoma has been consistently less than in Seattle and elsewhere in the region. There have been press reports of sharp debate over municipal vs. private collection and of allegations of inefficient service in some communities in the region, but none in Tacoma. Since 1970 the Refuse Utility has recommended two fee increases and one fee modification (the addition of the charge for extra bags). On each of these occasions the council was satisfied that the fee increases were justified. Each time, the council considered one proposal to abolish the

Refuse Utility in favor of private collection on a contract basis and another proposal to apply reduced rates for carryout service to elderly and disabled residents; both proposals were rejected each time by votes of 8 to 1.

MODEL AND RESULTS

To model the demand for solid waste collection services in Tacoma, I have employed both a multinomial logit model and a regression model. The multinomial logit model is used to characterize choices among the alternative levels of service offered in Tacoma while the regression model is used to explain data concerning total quantities of household waste generated.

Choice Among Alternative Services

As explained in the preceding section of this paper, Tacoma offers its residents a choice among a number of different collection services distinguished by the number of cans presented for collection and the location with respect to curbside at which these cans are presented. In all, approximately 16 different service levels are offered, ranging from 1 to 6 cans per collection at various distances from curbside.(3)

The basic hypothesis on which the statistical model of service selection used here rests is that the probability that any given subscriber will choose a given service level is related to certain attributes of that service level and certain individual characteristics of the subscriber. In the particular case at hand, the service attributes would be such things as its monthly cost, number of cans, and distance from the curb; subscriber characteristics would be such things as family size, income, and other household characteristics.

The available data report the frequency with which subscribers chose the different available services in each of 59 months spanning the period January, 1973 to November, 1977. The schedule of fees for the various available services changed once during this period (in January of 1975), and the charge for collection of extra bags was increased from zero to $0.75 per bag in May of 1976.

The model used here to characterize service choice data is the multinomial logit model of qualitative choice. This model, as noted above, expresses the probability that an individual will choose a given alternative as a function of the characteristics of the alternative available, the characteristics of the chooser, and interaction terms between alternative and choice-maker attributes. The basic form of the model is as follows:

$$(1)\qquad P_{ij} = \frac{e^{\alpha' X_i + \beta_i' Z_j + \gamma_i' W_{ij}}}{\sum_{i=1}^{M} \left(e^{\alpha' X_i + \beta_i' Z_j + \gamma_i' W_{ij}} \right)}$$

where P_{ij} = the probability that the jth individual will be observed to choose the ith alternative.

M_{ij} = number of alternatives.

α = $K_1 \times 1$ vector of parameters.

X_i = $K_1 \times 1$ vector of attributes of the ith attribute.

β_i = $K_2 \times 1$ vector of parameters.

Z_j = $K_2 \times 1$ vector of attributes of the jth individual.

γ_i = $K_3 \times 1$ vector of parameters.

W_{ij} = $K_3 \times 1$ vector of interaction variables formed from products (or other combinations) of alternative attributes and individual attributes.

This is the general form of the model I have estimated using data on service choices in Tacoma.

Before discussing the precise form of the model estimated and the statistical procedures employed, some explanation of why the multinomial logit model was chosen to characterize solid waste collection service choice may be in order. There are, in fact, two reasons. First, it can be shown that the logit model can be derived from a theory which explains the distribution of choices observed in a population of consumers with differential preferences. In particular, it can be shown that starting with some assumptions about the nature of consumers' preferences and the nature of the random differences that distinguish individual preferences, equation (1) can be derived by assuming that consumers choose the most preferred alternative available to them. The probability distribution implied by equation (1) may thus be interpreted as predicting the probability distribution of choices that would be made by a population of utility maximizing consumers. Second, among the alternatives available for modeling choice among distinct alternatives, the multinomial logit model is computationally the most tractable. These two factors -- consistency with economic theory and computational considerations -- have led to the choice of the multinomial logit.

Unfortunately, the data available are not adequate to estimate the logit model in its most general form (as shown in (1) above). In particular, the data contain no information on the characteristics of individual subscribers in Tacoma that could be matched with subscriber choices among services. My working assumption is thus that the distribution of these characteristics in the population has remained roughly constant over time, and that these characteristics can be treated as a part of the random variation in individual preferences. The remaining explanatory variables in the model are attributes of alternative services, including price, number of cans, and distance from the curb at which cans are placed.

Employing this specification, the unknown parameters of the model have been estimated using the method of maximum likelihood. Estimated parameters and asymptotic t-ratios are shown below in Table 1. As the results reported in Table 1 show, the fraction of the total subscriber population choosing any particular service declines with the cost of the service, the number of cans per collection the service provides, and the distance from the curb at which collection is offered. Taken at face value, these results suggest that households prefer lower levels of service (e.g., fewer cans relatively close to curbside), other things being equal. While this result may seem curious at first sight, many investigators have reported that households do not like backyard service (due to noise, spillage, unfamiliar persons in close proximity to the house) and do not care for the space and other management problems posed by additional cans. The negative signs of the coefficients of number of cans and distance from the curb could thus reflect these considerations.

Estimated price elasticities of demand for each of the services corresponding to the parameter estimates shown in Table 1 are reported below in Table 2. These estimates exhibit the pattern that elasticities increase with service levels. This is generally what one would expect. At higher levels of service, one has more alternatives to switch to in the face of a price increase. For example, households subscribing to two can service at a distance of between 25 and 75 feet could consider switching to one can service at this distance, to two can service in the curbside zone, or to one can service in the curbside zone. Households subscribing to two can service in the curbside zone can only reduce their service demanded by switching to one can service in the curbside zone.

Taken together, the results reported in Tables 1 and 2 suggest that the demand for solid waste collection service levels is sensitive to service price, and that pricing policy can have a very substantial effect on the number of households subscribing to higher levels of service.

Waste Generation

The results reported in Tables 1 and 2 above pertain to choices among the alternative collection services offered by the City of Tacoma. The other equations in my model of the demand for collection services in Tacoma are equations explaining the total quantity of waste generated by households in Tacoma. For these relationships, I have adopted regression equations relating estimated waste generated in Tacoma by households to the price of collection services, income (retail sales is used as a proxy for income), number of

TABLE 1. ESTIMATED PARAMETERS OF MULTINOMIAL LOGIT MODEL

Service characteristic	Coefficient estimate	Standard error	Asymptotic t-ratio	Gradient
Price	-0.486187	5.394209E-03	-90.1312	-599.292
Number of Cans	-1.00216	5.685739E-03	-176.259	-227.691
Distance From Curb	-0.091494	2.394175E-04	-382.152	-3209.7

TABLE 2. ESTIMATED PRICE ELASTICITIES USING MULTINOMIAL LOGIT MODEL

Service (number of cans, distance)	Price of service	Share of market	Estimated elasticity of demand
(1,1)	2.45	.7809	0.2610
(2,1)	3.60	.1639	1.4634
(3,1)	4.85	.0328	2.2807
(4,1)	6.00	.0069	2.8970
(5,1)	7.15	.0014	3.4714
(6,1)	8.30	.0003	4.0341
(1,2)	3.90	.0125	1.8724
(2,2)	6.55	.0013	3.1804
(3,2)	9.20	.0001	4.4725
(4,2)	11.85	.0000	5.7613
(1,3)	5.30	.0000	2.5768
(2,3)	9.35	.0000	4.5458
(3,3)	13.40	.0000	6.5149
(1,4)	6.65	.0000	3.2331
(2,4)	12.10	.0000	5.8829
(3,4)	17.55	.0000	8.5326

Distance key:
1 = 0-25 feet
2 = 25-75 feet
3 = 75-200 feet
4 = ≥ 200 feet

subscribers, and season. Three different equations have been estimated, one for each of the components of total waste generation. These three components are total residential collection, litter (which is assumed to be generated by households), and the estimated quantity of waste self-hauled by households for disposal at the city landfill. The estimated equations for each of these components of household solid waste are summarized below in Table 3.

In broadest terms, the results shown in Table 3 are consistent with what one would expect. Increases in the price of collection services tend to reduce the quantity of household waste presented for collection and to increasethe quantity of self-hauled household waste. Collection service price seems to have a small negative effect on litter that is practically insignificant. Note,however, that only in the equations fromself-hauling and collection is the price term significant at the 10% level.

Because of the fact that the regression equations reported in Table 3 were estimated in the natural logarithms of the variables shown, each coefficient may be interpreted as an elasticity. Interpreted in this fashion, the regression results imply a relatively low price elasticity of demand for quantity collected with respect to average collection charge of approximately 0.15. If collection charges were increased across the board by 10 percent, approximately a 1.5 percent reduction in quantity of waste presented for collection could be expected, and quantity self-hauled could be expected to increase by about 5.4 percent. Since self-hauling accounts for about 20 percent of household solid wastes and municipal collection accounts for about 80 percent (litter is a negligible fraction), the estimated percentage change in quantity generated associated with a 10 percent increase in price would be approximately zero (i.e., 0.2 x 5.4 - 0.8 x 1.5). This implies that the

TABLE 3. REGRESSION MODEL RESULTS (t-STATISTICS SHOWN IN PARENTHESES)

	log (tons of solid waste collected)	log (tons) of solid waste self-hauled)	log (tons of litter)
Constant	2.2861	20.4863	-6.4047
log(Deflated Average Service Price)	-0.1516 (-1.3626)*	0.5350 (1.2344)	-0.7120 (-0.6414)
log(Deflated Retail Sales)	0.0615 (0.3707)	-1.6283 (-2.5182)*	-2.2052 (-1.3314)*
log(Number of Subscribers)	0.5098 (1.7714)*	0.5658 (0.5046)	3.4908 (1.2154)
Winter Months Dummy Variable	-0.0745 (-2.9772)*	-0.7935 (-8.1399)*	-0.0114 (-0.0456)
Extra Bag Service Dummy Variable	-0.0319 (-1.4324)*	0.1690 (1.9458)*	-1.3446 (-6.0437)*
$\overline{R}^2$	0.1576	0.6224	0.5402
F(5,41)	2.721	16.167	11.808
D.W.	2.06	1.70	1.87

* Significant at the 0.10 level.

main effect of increases in the price of solid waste collection services is to increase self-hauling. There is no reduction in quantity of waste generated according to these results.

The coefficients of the proxy used to represent income -- retail sales -- indicate that self-hauling and littering are negatively associated with income levels, and that quantity presented for collection is associated positively (but weakly) with income. The retail sales variable is statistically significant, however, only for self-hauling and littering, with self-hauling and littering decreasing with retail sales.

Increases in the number of subscribers (which is equal to the number of households in Tacoma) result in increases in all three components of the household waste stream. Our estimates for collection and self-hauling (only the coefficient in the collection equation is significant at the 10 percent level) imply that waste has increased less than in proportion to the number of subscribers. Our estimate for littering suggests that this component has increased at over three times the rate of increase of households, other things being equal. As has been suggested above, however, littering is an insignificant portion of the total, and may not have been household litter. In addition, the coefficient of number of households is not statistically significant.

The coefficient of the dummy variable for the winter months indicates that less waste is presented for collection and less is self-hauled during the winter months than during other months of the year. This probably reflects seasonal patterns in household waste generation, particularly with respect to yard wastes.

The coefficient of the dummy variable representing the formal introduction of extra bag service and associated increase in the price of this service in 1976 suggests that the price increase reduced household collection and increased self-hauling, and reduced littering (perhaps by providing a ready means to dispose of temporary excess wastes).

To sum up, the statistical results presented in this section show that the choice of service level is sensitive to price, and that choices are somewhat more responsive to price changes at relatively high service levels. This is, I hypothesize, because there are relatively more substitution alternatives available to households at high levels of service (i.e., they either can reduce the number of cans per collection, or the distance from the curbside at which cans are presented for collection, or they can self-haul). My results also suggest that the quantity of waste generated seems to be relatively insensitive to price. However, the choice between collection and self-hauling does seem to be sensitive to price.

Let me hasten to caution that the results presented are far from conclusive. The data available are relatively rough, and the statistical procedures and assumptions I have made in modeling them by no means are the only ones that could be adopted. If these assumptions or modeling methods were changed, it is quite possible that the results would change also.

CONCLUDING REMARKS

Keeping firmly in mind that all of the statistical results reported in this paper are tentative, it is still useful to discuss the implications for solid waste management which follow from my results. Certainly the strongest implication is that user charges can be used to affect the demand for levels of service. Increasing prices on high service levels seem to result in a reduction in the number of households choosing high service levels. To the extent that provision of high service levels is uneconomic, such a charging policy can increase the economic efficiency of solid waste management.

Some idea of the overall difference in demand for services under a graduated user charges policy, like that employed in Tacoma, and under a flat rate policy can be gotten by comparing predicted service demands under these two charge systems. This is done in Figure 1 below, where predicted percentages of subscribers are shown on the vertical axis, and the various

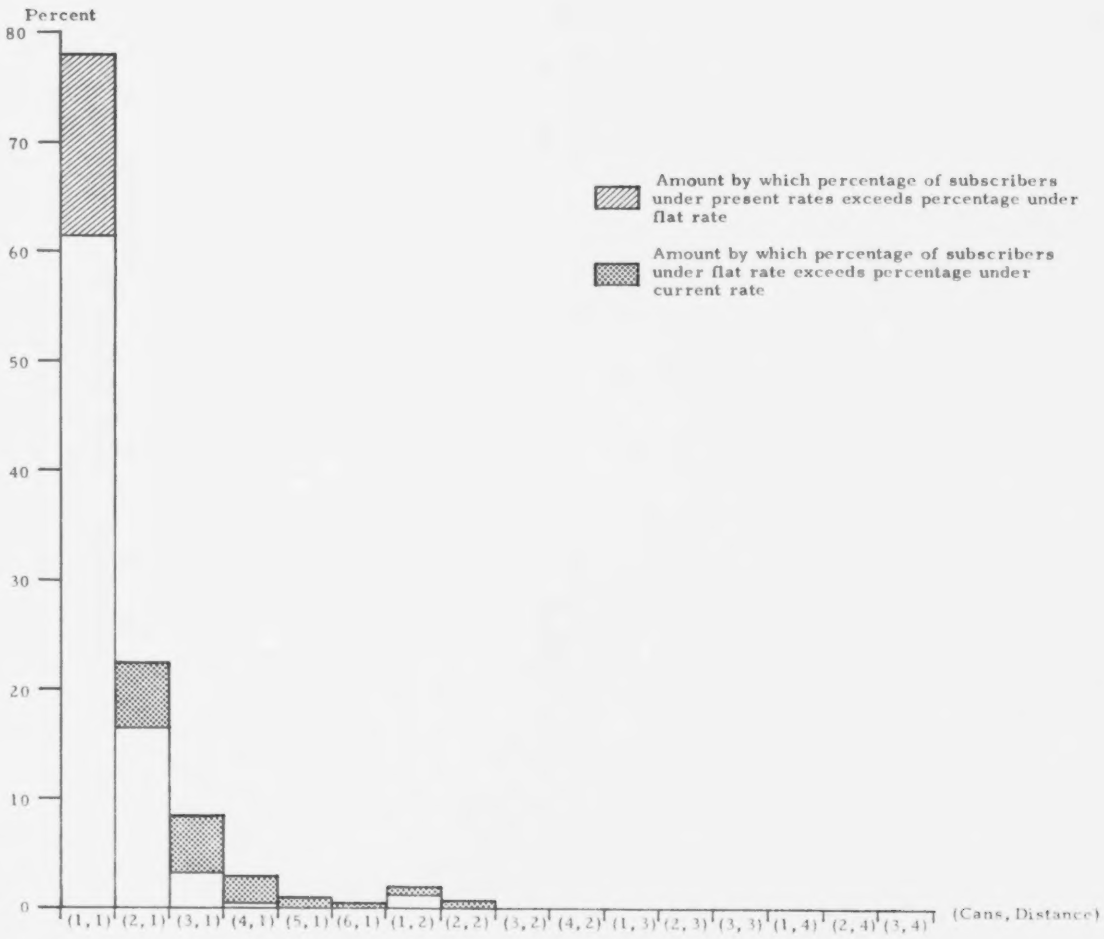


Figure 1. Percentage of households at each service level under present charge rates and under a flat rate system.

can/distance combinations that constitute the available services in Tacoma are shown on the horizontal axis. As can be seen in Figure 1, the percentage of households subscribing to basic service is estimated to be about 17 percentage points higher under Tacoma's current graduated charge policy (see the diagonally shaded area in Figure 1). These 17 percentage points reflect a predicted shift away from higher levels of service. The predicted net percentage shifts from each of the higher levels of service are shown by the stippled areas in Figure 1.

These calculations suggest that the aggregate effect of pricing policy on service level choice may be quite large. If the costs of providing higher service levels are large, this suggests that the efficiency gains from adoption of a cost-based pricing policy could be substantial.

A second implication of my results is that service prices have little effect on the quantity of waste generated by households. While my results do show some tendency to reduce tonnage placed for collection, they also show an approximately equal increase in tonnage self-hauled to the landfill.

Overall, these results support the proposition that households' demands for solid waste collection and disposal service are sensitive to price. In addition, these results suggest that the degree of sensitivity may be quite high, and therefore that the solid waste management efficiency gains typically ascribed to a user charge policy that sets charges equal to service costs may be correspondingly great.

NOTES AND CITATIONS

(1) I am indebted to Fritz Efaw of MATHTECH for his able collection of the data for this study under EPA Contract No. 68-03-2634.

(2) Stevens, Barbara. "Pricing Schemes for Refuse Collection Services: The Impact on Refuse Generation." Research Paper No. 154, Graduate School of Business, Columbia University, New York, New York, January 1977.

(3) Virtually no subscribers elected options to have "flight of stairs" service. These options are therefore ignored in my analysis.

THE DESIRABILITY OF COMMODITY FUTURES TRADING IN SCRAP MATERIALS

Roger C. Dower and Elizabeth H. Granitz
Environmental Law Institute
1346 Connecticut Ave., N.W.
Washington, D.C. 20036

ABSTRACT

The highly variable prices for many secondary materials introduce uncertainty concerning future prices for these commodities. This price uncertainty tends to act as a barrier to the consumption of scrap materials. This paper proposes commodity futures trading in scrap materials, especially wastepaper and ferrous scrap, as a means of lessening the impacts of future scrap price uncertainty. By providing a market for managing the risk associated with price uncertainty, and by increasing the flow of futures market information. futures markets in secondary materials should result in increased demand for secondary materials, improved credit terms for traders in the market, and a greater level of investment in scrap processing.

In order for a futures market in scrap to be an effective hedging device and to provide reliable future market information, it must be shown that scrap commodities can be successfully traded. Several characteristics of the markets for commodities in which there is successful futures trading are enumerated and are compared with the markets for wastepaper and ferrous scrap. In general, the market for ferrous scrap appears to satisfy the requirements for successful trading if the important grades of scrap can be more rigorously specified. The case for futures trading in wastepaper is not as clear.

INTRODUCTION

Secondary material or scrap markets are characterized by unusual price volatility. By all accounts, this price variability hinders investment in the secondary materials industry and adversely affects recycling levels in the wastepaper and ferrous scrap industries. This paper, drawing on research performed for the U.S. Environmental Protection Agency, presents the case for a futures market in wastepaper or ferrous scrap as one alternative for mitigating the impacts of scrap price volatility and thereby increasing the level of recycling.

The format for this paper follows the report entitled, "An Analysis of Scrap Futures Markets for Stimulating Resource Recovery."(1) First, the underlying causes of variable scrap prices and the resulting price uncertainty are discussed and the groundwork for the evaluation of futures markets is laid. The next two sections introduce the concept of futures trading in secondary materials by summarizing the mechanics of futures trading, presenting the potential economic impacts of futures trading, and comparing the characteristics of several existing futures contracts to those for scrap materials. The final section of the paper provides a brief analysis of the probable effects of scrap futures trading on the supply and demand responses of both participants and non-participants in the market.

UNCERTAINTY AND RESOURCE ALLOCATION IN SECONDARY MATERIALS MARKETS

Causes of Price Uncertainty for Secondary Materials

The basic cause of the variation in

secondary materials prices, and therefore the high level of price uncertainty, can be found in the inelastic demand and supply schedules for these materials. Prices tend to be more variable when demand and supply functions are unresponsive to price and when they are subject to large shifts. This situation is demonstrated in Figure 1. A shift in demand from D to D^1 does not lead to such a large change in price in Panel A, where the supply function is relatively elastic, as it does in Panel B where both the demand and supply functions are inelastic.

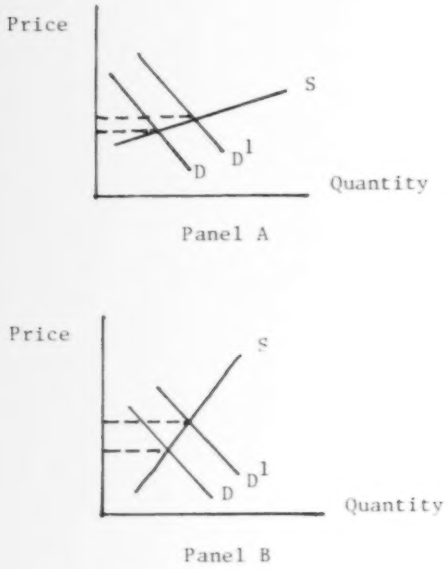


Figure 1. Variation in market prices.

Elasticities for secondary materials tend to be quite low, particularly when compared to demand and supply elasticities for primary materials. Elasticity estimates for secondary and primary materials are reproduced in Table 1.

Economic theory demonstrates that the elasticity of demand for an input to production processes depends upon: (1) the number and availability of substitute materials; and (2) the cost of the input relative to the selling price of the final output. Neither of these reasons is sufficient to explain the low elasticities for secondary inputs.

TABLE 1. SUPPLY AND DEMAND ELASTICITIES FOR SECONDARY MATERIALS*

Material	Supply Elasticity	Demand Elasticity$^+$
Wastepaper	0.40	0.08
Wood pulp	NA	NA
Scrap steel	1.12	0.64
Pig iron	NA	NA
Secondary lead	0.48	0.21
Primary lead	1.00	
Scrap copper	0.32	0.87
Primary copper	1.67	

*References: Wastepaper(2)
Scrap steel(2)
Lead(3)
Scrap copper(4)
Primary copper(5)

$^+$For secondary lead and scrap copper, the demand elasticity refers to the industry demand curve for primary and secondary inputs combined.

NA: not available.

There are two other, more relevant, reasons for the low demand elasticities for secondary inputs. First, many users of primary and secondary inputs are vertically integrated into primary material supply sources as insurance against uncertainty in input availability and possibly for favorable tax treatment specific to primary production. This provides an incentive to rely upon primary inputs in preference to secondary materials. Second, demand for scrap inputs is closely tied to capacity cycles in the paper and steel industries. Firms that normally use primary inputs will increase their demand for secondary inputs when, because of upward swings in the business cycle, their capacity to produce the primary inputs is strained. A decline in the demand for paper and steel products shifts the demand for scrap inputs back to more normal levels. The two-level demand structure and the vertical integration of user mills implies that the demand for secondary materials will be less elastic and subject to larger fluctuations than would be the case for primary materials.

The low supply elasticities are due in part to (1) rising costs as marginal supplies of scrap are brought to market, (2) the fact that most prompt industrial scrap is sold irrespective of price, and (3) the low level of inventory holdings by user mills and scrap dealers/processors.

The Impact of Price Uncertainty on Resource Allocation

In the face of uncertainty over output price, output and input use levels will be lower than under certain demand or price conditions(6,7). Therefore, because of uncertainty over secondary materials prices, output from the scrap processing or dealer sector will be less than if scrap prices were known with certainty. In terms of scrap consumers, uncertainty over expected prices for scrap materials introduces difficulty in making rational short-run production and inventory decisions, and reduces the reliance on secondary materials as inputs to production processes. Uncertainty over present and future prices for scrap has been cited as a major deterrent to increased recycling of wastepaper and ferrous scrap.(8,9)

The impact of uncertainty is exacerbated in the scrap markets by the inability of producers or consumers to protect themselves from the inherent risk of an uncertain market environment. Forward contracting and vertical integration, two common market mechanisms for mitigating the effects of demand and supply uncertainty, are not viable alternatives for the scrap markets. In addition, price variability and the inability to cope with price risk, creates instability in industry profits and adversely affects the ability of scrap producers and consumers to obtain funds from lending institutions and capital markets.

The stage is now set for the examination of alternative policy options designed to rectify the imbalance between secondary and primary materials use caused by price uncertainty in scrap markets. The following sections of this paper argue that an organized scrap futures market would provide a means of forward trading in the affected commodities, would generate future prices, and would allow industry members to hedge some of the price risk in the markets for secondary materials.

FUTURES MARKETS AND THEIR ECONOMIC IMPACT ON THE CASH MARKET

Futures Markets

Futures markets differ from other markets (for example, cash, contract, or forward delivery markets) on a number of counts.(10) (1) A futures contract, which calls for delivery of a commodity at some future date, is standardized as to quality and quantity as well as other terms of delivery. (2) Futures contracts are traded on organized commodity exchanges under rules promulgated by the exchange. For example, the copper contract traded on the Commodity Exchange, Inc. in New York calls for delivery of 25,000 pounds of 99.9 percent pure copper cathodes. The delivery months are January, March, May, June, July, September and December. Delivery can be made from any one of six Comex warehouses located across the country. (3) Futures markets are impersonal markets in that buying and selling is done through a clearing house, which is generally a part of the exchange. (4) Futures markets are extremely competitive markets. All trades are made by open outcry in the specified trading area, or "pit," of the exchange. (5) Although it is a legally binding commitment to deliver or purchase a commodity, a futures contract does not transfer title to the commodity. A long position, if a contract has been sold, can be liquidated by taking delivery of the commodity or by taking an offsetting position in the market. (6) Although deliveries can be made on futures markets, generally buyers and sellers are better off negotiating a cash market transaction since the terms of delivery on the futures market do not usually represent the most profitable terms for actual sale or purchase. Many contracts traded on futures markets experience less than 1 percent delivery rates.

Economic Impacts of Futures Markets

The economic impacts of futures trading can be divided into three general categories: (1) cash market pricing impacts; (2) risk management impacts; and (3) market information impacts. Each of these will be discussed below.

Pricing Function of Futures Markets--

By serving as a central market place for commodities, futures markets lower the transaction costs of trading in an uncertain market environment. Traders buy and sell futures contracts based on their expectations concerning current and future demand and supply conditions. The competitive nature of futures markets assures that the futures prices will be unbiased predictions of future cash prices.(11) By providing a forum for the assimilation and dissemination of market information and expectations, futures markets have been termed price discovery mechanisms.

The futures prices signal decisionmakers when to produce, consume, or hold stocks and, in a sense, regulate production and consumption of the commodity.(12) Theoretically, then, futures markets should stabilize cash market prices as the futures prices are translated into more orderly transformations of market positions. Attempts to verify this theoretical impact have reached differing conclusions(13, 14 15,16,17). In general the models and techniques used have not been able to account for other structural changes that may have influenced cash price variation. In an analysis of the impact of futures trading on the responsiveness of plywood supply to price signals prepared for this study, it was shown that supply response for plywood increased after the initiation of futures trading. In other words, with a futures market a given change in price would result in a larger change in the quantity of plywood supplied.

On the other hand, it has been argued that the speculative activity in futures markets has a destabilizing effect on cash prices. Theoretical and empirical studies do not support such an effect.(18,19) If speculators base their buying and selling strategies on the best available market information, they should actually act to stabilize cash prices at their true value.

The Risk Management Function of Futures Markets--

There are two types of direct participants in futures markets: speculators and hedgers. Speculators buy and sell futures contracts in hopes of profiting from favorable movements in the future prices; they have no position in the cash market and rarely intend to make or take delivery on the futures market. Speculators add liquidity to a futures market by making it easier for hedgers and other traders to establish market positions and thus help to assure a well functioning marketplace.

Hedgers are generally commercial buyers or sellers of commodities traded on futures markets, or closely related commodities, and use the futures market to manage the risk of an unfavorable movement in the cash price that would affect a position they hold or plan to hold in the cash market. A hedge consists of taking an opposite position in the futures market from one held in the cash market. Since near futures prices and the cash price of a given commodity tend to move together, a loss in one market can be offset by a gain in the other. As long as prices for a commodity and the futures prices for another commodity are highly correlated, the former can be hedged against the latter. The hedging of copper scrap against the copper contract traded in New York or London is an example of this type of hedging.

Table 2 illustrates a hypothetical buying hedge, the purpose of which is to establish a forward price for a planned or actual commitment in the cash market. A copper scrap dealer with no scrap on hand enters into a contract to provide 25,000 pounds of #2 copper scrap to a user in two months at 48.5¢ per pound. To hedge the risk of the cash price for copper scrap rising over the period, he buys a July copper contract for 64.2¢ per pound. At the end of the two month period the price of copper scrap has risen 2¢ a pound and the scrap dealer is forced to take a loss of that same amount on his cash market transaction. However, inasmuch as the futures contract price will also have risen by about two cents, he can sell his July contract for more than what he paid for it. His gains and losses are nearly matched.

A simple selling hedge, which enables a commercial trader to protect inventory holdings, is illustrated in Table 3. In April the dealer buys 25,000 of #2 copper scrap at 48.5¢ per pound and sells a July copper futures at 64.2¢ per pound. Suppose that by June the cash price of the scrap has dropped to 48.5¢ and the dealer sells his inventory at a loss of 2¢ per pound. At the same time, he will be able to buy back the futures contract for about 2¢ more than what he paid for it. Again, the net loss is zero.

TABLE 2. EXAMPLE OF A BUYING HEDGE

Item Activity	Cash	Futures
April:		
Buy	--	July 64.2¢
Sell	48.5¢	--
June:		
Buy	50.5¢	--
Sell*	--	July 66.2¢

*Loss, 2.00¢; gain, 2.00¢; net loss, 0.

TABLE 3. EXAMPLE OF A SELLING HEDGE

Item Activity	Cash	Futures
April:		
Buy	48.5¢	--
Sell	--	July 64.2¢
June:		
Buy	--	July 62.2¢
Sell*	46.5¢	--

*Loss, 2.00¢; gain, 2.00¢; net loss, 0.

Although actual hedging decisions will depend on a host of factors, these simple examples serve to demonstrate the risk management function of futures markets. Where risk is defined as variance in income and variation in income arises from price fluctuations, a rational hedging program will increase income stability for producers and consumers(20).

Market Information Effects of Futures Trading--

Traders in futures markets use information from numerous sources (exchange and commission house publications, government agencies, etc.) to form expectations concerning future market conditions. This information is reflected in the futures prices generated by their trading activities. These prices are reported in the media and are available to all market participants. Widely disseminated price information should lead to a more responsive marketplace. The ability of futures markets to increase the normal flow of market information results from: (1) the provision of a central marketing place; (2) an increase in competition in the market; and (3) lower transaction costs of information exchange. As a result "market prices provide more accurate signals for resource allocation when there is futures trading in a commodity."(21)

FUTURES TRADING IN SECONDARY MATERIALS

The ability of any futures market to generate the types of economic impacts discussed above is highly dependent on how successfully the market works.

Although the various criteria used to judge whether a commodity can be successfully traded on a futures market tend to be vague, it is possible to identify several characteristics that are important in determining the success of a futures contract. General characteristics are presented first, followed by the application of more specific criteria for futures trading in scrap materials.

General Elements Necessary for Successful Futures Trading

In a broad sense, a successful futures contract can be defined as one in which there is sufficient trading volume to ensure continued listing of the contract by the exchange. To ensure hedging demand there must be a reason for buyers and sellers to want to use a mechanism to manage price risk. Hedging demand is also a function of the ability of an exchange to design a standard contract for trading that follows accepted industry practices in terms of quality, quantity, and specification of delivery. Furthermore, there must be a general industry acceptance of the futures market. Ill-informed or misconceived notions concerning futures trading may result in a lack of hedging volume. Once hedging demand is established, speculative trading demand tends to follow.

While it is clear that a need exists in the wastepaper and ferrous scrap markets for some type of risk management tool, general agreement among industry members that futures markets represent a practical, or even desirable alternative is lacking. These doubts typically result from the fears that a futures market would supercede the normal marketing procedures for scrap, and that speculators would enter the market and drain industry members of their profits.

Specific Elements for Successful Futures Trading

Competitive Market Place--

To minimize the possibility of either buyers or sellers controlling the market for a commodity, competition should prevail among both buyers and sellers. Lacking complete knowledge of the structure, conduct and performance of the firms in the scrap industry, the concentration ratio is a useful proxy for evaluating the competitiveness of the wastepaper and ferrous scrap industries. Table 4 lists the four-firm concentration ratios for different sectors of the steel, and pulp and paper industries for 1967 and 1972. Using Guthrie's criteria, that in industries where economies of scale are substantial concentration ratios of less than 30 indicate competitive conditions, it is concluded that all sectors in the paper and steel industries are relatively competitive, except for pulp mills, sanitary products, blast furnaces and steel mills. (22) The intense foreign competition for ferrous scrap undoubtedly increases the competition in the blast furnace sector with respect to scrap purchases.

Although no concentration ratios are available for the seller or scrap dealer side of the markets in wastepaper and ferrous scrap, it appears that this sector fits well into the competitive mold. Of the approximately 1800 firms in the U.S. ferrous scrap industry, over 80% of the firms have output volumes of less than 30,000 tons. (23) In 1963, there were some 2700 wastepaper dealers in the U.S., most of whom were located near a few major cities.

Standard Contract Grade--

A futures contract must define a homogeneous quality of the commodity to be delivered. The delivery grade must be specified within small tolerances, be testable, be acceptable to members of the industry, and be representative of a sizable portion of the commercial transactions in the cash market for the particular commodity. The standardization of the commodity to be delivered assures that each buyer knows exactly what grade and quality of the commodity will be delivered.

There is an apparent consensus among industry members and commodity exchange officials that the specification guidelines which are now used in the wastepaper and ferrous scrap industries are not sufficiently rigorous to be of use in designing a futures contract. A solution to this problem is for scrap buyers, sellers, and exchange officials to meet and outline formal, concise tolerances in terms of allowable contaminant levels, and then formulate descriptions for at least the major grades of wastepaper and ferrous scrap. No. 1 Heavy Melting or No. 1 Bundles, appear to be appropriate grades for ferrous scrap futures contract. They are relatively homogeneous, have a history of use in the industry, have a great deal of buyer confidence, and account for a large portion of the commercial transactions in ferrous scrap. For a wastepaper futures contract, one of the six or seven grades of corrugated materials could be chosen for trading. Corrugated medium is an important component of wastepaper, accounting for approximately 40 percent of all wastepaper consumed in the manufacture of paper and paperboard. (25)

TABLE 4. CONCENTRATION RATIOS FOR SELECTED SECTORS OF THE PULP AND PAPER, AND STEEL INDUSTRIES (4 FIRM RATIOS)*

Item	1967	1972
I. Paper and Pulp:		
Pulp Mills	45	59
Paper Mills	26	24
Paperboard Mills	27	29
Sanitary Products	63	63
Folding Boxes	22	28
Set-up Boxes	12	11
Corrugated and Solid Fiber Boxes	18	18

TABLE 4 continued

Item	1967	1972
II. Steel		
Blast Furnaces and Steel Mills	48	45
Steel Pipes and Tubes	26	23
Grey Iron Foundries	27	24
Steel Foundries	NA	24
Steel Wire and Related Products	24	18

*Reference(24).

Initially, trading in a wastepaper or ferrous scrap futures contract should be confined to one grade so that buyers of the contracts will have confidence of receiving the par grade on futures market deliveries. A single grade contract would still be of use to buyers and sellers of other grades to the extent that the prices for different grades of wastepaper and ferrous scrap move together closely. The contract could still be used for hedging, and the trader need never consider making or taking delivery on the market.

Correlation analysis performed on the price series for individual grades of ferrous scrap and wastepaper showed that the different grades of iron and steel scrap are highly correlated, while the individual grades of wastepaper are not so closely correlated. A ferrous scrap futures contract in one grade could be used to hedge against other grades, whereas the case for wastepaper is not that clear. Trading separate contracts in each grade of wastepaper may be feasible, but it would reduce the number of buyers and sellers in any one contract and thus impair the liquidity of the market.

Standard Pricing and Delivery Arrangements--

For a futures market to be an effective hedging device, the futures price in the month of delivery must converge with the cash price. Although deliveries on futures markets are relatively uncommon, it is the threat of delivery that forces the futures price and cash price to be equal during the delivery month. If they are not equal, traders will make or take delivery to take advantage of the price differentials until they do become equal. Therefore, the terms of delivery on a futures market are important in assuring the success of a futures contract.

Delivery on a futures market is instituted at the seller's discretion any time during the final month of trading in the contract by presenting to the buyer, through the clearinghouse, a warehouse receipt if the commodity is being delivered out of inventory or storage, or a shipping certificate if delivery is from current production. The contract stipulates which delivery instrument is to be used. The shipping certificate would seem to be the appropriate delivery instrument for a futures contract in wastepaper or ferrous scrap, since dealer inventories of these materials are held for only short periods of time.

Futures markets traditionally use one of two types of pricing arrangements: (1) delivered to the market city, if the seller normally assumes responsibility for transportation costs; or (2) F.O.B. a natural shipping point if the buyer usually pays for transportation. Ferrous scrap transactions almost always have the seller paying transportation charges. For wastepaper there seems to be no standard industry procedure. Generally, longer-distance hauls of higher grades of wastepaper are shipped with the seller assuming the transportation costs. Pricing delivered to the market city is recommended for both ferrous scrap and wastepaper.

There are four main criteria for selecting a base point from which prices will be established: (1) there should only be one base point; (2) the base point should be a natural merchandizing channel for the commodity; (3) it should be a natural loading point for shippers; and (4) storage and/or production facilities should exist so that physical delivery can be made at a known cost.(26) Although no central marketing place exists for wastepaper and ferrous scrap, the markets for these commodities are highly concentrated. Wastepaper buyers and sellers are concentrated between Philadelphia and Boston, with another large market in Chicago. Any one of the large cities within this region could be used as a base point. It has been suggested by commodity exchange officials that New York would be appropriate. Ferrous scrap dealers and users are concentrated in and around Pittsburgh. Pittsburgh would be a likely candidate as a base point for pricing and delivery of ferrous scrap.

Inspection procedures for commodities traded on futures markets vary widely. An exchange, in designing inspection terms for a contract, will attempt to follow accepted industry procedures. In the ferrous scrap and wastepaper industries, the buyer generally has the right to inspect and grade all purchases. The seller has the option of accepting the decision of the buyer or taking his materials elsewhere. Ferrous scrap inspections depend on the grade of scrap supposedly being delivered; the higher the grade the less inspection. Wastepaper deliveries are usually only visually inspected. For the buyer, the major criteria in determining how far to carry the inspection depend on the past performance of the seller.

When it formulates inspection procedures for a scrap futures contract, an exchange must make certain that these procedures are fair and do not favor one side of the market over the other. Random inspections, by a private agency, of those sellers who are allowed to deliver on the futures market may be one alternative to ensure fairness.

IMPACTS OF FUTURES TRADING ON MARKETS FOR SECONDARY MATERIALS

The class of individuals and organizations whose profit-maximizing behavior would be affected by futures trading in scrap can be divided into two groups: (1) direct participants; and (2) nonparticipants in futures trading. The first group includes scrap dealers and scrap consuming mills who would use the risk management function of futures markets. The second group, or nonparticipants, are those members of the scrap industry who use the market information generated by futures markets to make inventory and production or consumption decisions.

Participants

Hedging in a futures market is consistent with sound business practices. A futures market in wastepaper or ferrous scrap would enable buyers and sellers in those materials to hedge their present and future cash positions and to thus remove that element of business risk associated with uncertain prices of the product. The resulting increase in producer and consumer income stability would improve scrap dealers' and consumers' access to capital since it would lower the risk premium demanded by lending institutions and financial markets. Hedging may be of additional use to scrap-consuming mills in that it would help them to reduce quantity/availability uncertainties as well as price risk.

Nonparticipants

One of the principal functions of a futures market is its forward price discovery role. The forward or futures prices are published daily and are available to nonparticipants as well as futures market traders. The forward prices represent unbiased estimates of the prices that will prevail at a future date. To the extent that these prices are used in forming dealer and user price expectations, they will affect inventory decisions, production plans, and investment programs.

CONCLUSIONS

Our study suggests two crucial, but not insurmountable barriers to futures trading in wastepaper and ferrous scrap. These are as follows. (1) A standard contract grade that is acceptable to industry members must be defined. Specification of a tradeable ferrous scrap grade may be easier than defining a wastepaper contract grade; the current grade specifications for ferrous scrap appear to be more concise and more widely accepted than those for wastepaper. (2) A sound futures trading information base must be established among industry members so that a hedging demand for a scrap futures contract is assured. Until scrap consumers and producers fully understand how futures markets can be used to their advantage, there will be insufficient demand for the services of such a market.

In the long run, a successful scrap futures market should lead to: (a) a greater reliance on secondary materials, at least those for which there is futures trading, as inputs to production processes;

(b) improved credit terms for firms that use the futures market for hedging purposes; and (c) increased levels of investment in scrap processing, both by scrap dealers and user mills. If organized futures trading in scrap is instituted, and if the obstacles mentioned above are overcome, it is likely that the supply of scrap from dealers and the demand for scrap by user mills will shift outward and become more elastic. The net effect on scrap markets would be greater price stability and an increase in the quantity of scrap recovered and reused.

REFERENCES

1. Anderson, R. C. and R. C. Dower. An Analysis of Scrap Futures Markets for Stimulating Resource Recovery. EPA-600/8-78-019.

2. Anderson, R. C. and R. D. Spiegelman. "Tax Policy and Secondary Material Use." *Journal of Environmental Economics and Management* 4 (1977): 68-82.

3. Anderson, R. C. "Economic Incentives for the Recovery of Secondary Land." *Resource Recovery and Conservation*, 2 (1977): 193-209.

4. Fisher, F. M.; P. H. Cootner; and M. N. Bailey. "An Econometric Model of the World Copper Industry." *Bell Journal of Economics and Management Science* 3 (1972): 568-609.

5. Pickard, W. C. and R. J. Krumm. "Joint Aluminum - Copper Forecasting Model," *Proceedings of the Council of Economics* of the American Institute of Mining, Metallurgical, and Petroleum Engineers, 1977.

6. Sandmo, A. "On the Theory of the Competitive Firm Under Price Uncertainty." *American Economic Review* 61 (1971): 65-73.

7. Stevens, G. Y. "On the Impact of Uncertainty of the Value and Investment of the Neo-classical Firm." *American Economic Review* 64 (1974): 319-36.

8. Albrecht, O. W. and R. G. McDermott. *Economic and Technological Impediments to Recycling Obsolete Ferrous Solid Waste*. Springfield, Va.: National Technical Information Service, PB 223-034, 1973.

9. Battelle Columbus Laboratories. *A Study to Identify Opportunities for Increased Solid Waste Utilization*, vol. 8. Prepared for the U.S. Environmental Protection Agency. Springfield, Va.: National Technical Information Service, PB 212-731, 1972.

10. Gray, R. W. *The Feasibility of Organized Futures Trading in Residential Mortgages*. Federal Home Loan Mortgage Corporation Monograph No. 3. Washington, D.C., 1974.

11. Gray, R. W. and D. J. S. Rutledge. "The Economics of Commodity Futures Markets: A Survey." *Review of Marketing and Agricultural Economics* 39 (1971): 57-108.

12. Peck, A. E. "Futures Markets, Supply Response, and Price Stability." Ph.D. diss., Stanford University, 1973. Ann Arbor, Mich.: Xerox University Microfilms, 1973.

13. *Ibid*.

14. Working, H. "Price Effects of Futures Trading." *Food Research Institute Studies* 1 (1960): 3-31.

15. Gray, R. W. "Onions Revisited." *Journal of Farm Economics* 45 (1963): 273-76.

16. Johnson, A. C. *Effects of Futures Trading on Price Performance in the Cash Onion Market*. U.S. Department of Agriculture, Economic Research Service, Technical Bulletin No. 1470, 1968.

17. Powers, M. J. "Does Futures Trading Reduce Price Fluctuations in the Cash Markets?" *American Economic Review* 60 (1970): 460-64.

18. Labys, W. C. and C. W. J. Granger. *Speculation, Hedging and Commodity Price Forecasts*. Lexington, Mass.: D.C. Heath and Company, 1970.

19. Brinegar, C.S. "A Statistical Analysis of Speculative Price Behavior." *Food Research Institute Studies* 9

(1970): supplement.

20. McKinnon, R. I. "Futures Markets, Buffer Stocks, and Income Stability for Primary Producers." *Journal of Political Economy* 75 (1967): 844-61.

21. Cox, G. C. "Futures Trading and Market Information." *Journal of Political Economy* 84 (1976): 1215-37.

22. Guthrie, J. A. *An Economic Analysis of the Pulp and Paper Industry*. Pullman, Wash.: Washington State University Press, 1972.

23. Regan, W. S., R. W. James, and T. J. McLean. Identification of Opportunities for Increased Recycling of Ferrous Solid Waste. Prepared by the Institute for Scrap Iron and Steel for the U.S. Environmental Protection Agency. Springfield, Va.: National Technical Information.

24. U.S. Department of Commerce, Bureau of the Census: *Census of Manufacturers*, 1976 and 1972.

25. American Paper Institute. *1976-1979 Capacity: Paper, Paperboard, Woodpulp Fiber Consumption*. New York, 1977.

26. Marcom, Inc. *Standardization of Transportation Costs for Futures Trading of Coal on a Commodities Exchange*. Prepared for the Federal Energy Office. Springfield, Va.: National Technical Information Service, PB 245-398, 1975.

AN ECONOMIC ANALYSIS OF PAPER RECYCLING

Roger Bolton
William College
Williamstown, Massachusetts

ABSTRACT

A useful, although partial and incomplete, framework for analyzing paper recycling is a review of various market imperfections which make the amount of paper recycling less than socially desirable, or less than "optimal," in terms of economic theory. The most common imperfections are felt to be: uninternalized pollution which is greater in production of paper from virgin pulp than from waste paper; discriminating taxation in favor of virgin sources; uncertainty in returns from investment in recycling and use of recycled paper, which inhibits investment; implicit subsidization of disposal of waste paper after a single use, due to the failure to price accurately solid waste disposal activities; biases, on the part of paper company managers, against use of waste paper. I review briefly these imperfections, the implications for policy, and some needed directions in new research. Public policy should continue to move toward elimination of the imperfections, but if that is not possible "second best" arguments exist for introducing subsidies to recycling to offset the imperfections. However, these arguments must be used cautiously.

INTRODUCTION

In this paper I plan to review generally one frame work for an economic analysis of paper recycling. I organize my discussion around some market "imperfections" which are widely assumed to make the level of recycling less than socially desirable, particularly relative to use of virgin pulp and relative to disposal of paper after a single use. In addition to reviewing the imperfections and the implications for government policy, I suggest some directions for new research. Indeed, the suggestions for research are the main point of my paper.

This approach is necessarily partial and incomplete. The literature on paper recycling is enormous, and it would do little good here to review it, or to introduce one more version of the ubiquitous flow diagram or a precise definition of "recovery," or to report on the latest data on prices and quantities. Ample sources are already available on that. Particularly good overviews of the economic analysis are found in (3,9,25,30, 31,35,43). My primary goal here is to focus attention on some needed directions for further research.

(I intend to limit myself to recycling of paper as paper, rather than as energy. This is partly for convenience, but for other reasons as well. The imperfections I focus on affectly mostly the choices between virgin pulp and waste paper in manufacture of paper products, although the imperfection in solid waste disposal pricing also affects energy recovery. On the supply side, policies to affect reuse as paper must operate on paper before it becomes part of "mixed solid waste;" the technology for recovering paper fiber from MSW produces very low grade products with limited markets (45,49). If paper is diverted before it becomes MSW, reuse as paper is far more valuable than reuse as energy.

(44). This is greatly reinforced by the fact that reuse as paper is quite consistent with energy recovery anyway; paper reuse merely postpones, but does not prohibit, eventual recovery as energy (44, 49). And a big increase in recycling would still not reduce the fuel value of the remaining MSW much (48). On the other hand, if paper can be recycled only after it becomes MSW, energy recovery seems the only possibility for large scale reuse and it is what policy should focus on. Thus, in a sense reuse as paper and energy recovery are not very inconsistent in the long run, even when reuse as paper does not dominate. To the extent recycling is economical at all, policy should work toward reuse as paper and prevent it from becoming part of MSW. For paper which does not become MSW, policy should encourage energy recovery to the extent it is economical.

An economist necessarily views recycling in the total context of resource allocation. He does not see it as solely a solid waste problem alone, or a resource problem alone, as some government reports may do (42). He does not see recycling, or anything else, as an absolute good. It provides no direct consumer satisfaction, but is a production process--rather, a sequence of processes--for the production of paper products. As such, it has alternatives, and the economist asks whether under existing markets and policies there is an appropriate balance between recycling and the other processes. He may also ask whether the total quantity of paper products is appropriate, and how recycling affects that.

The economist evaluates the relative quantities of different goods and the relative reliance on different production processes. Depending on markets and policies, there can be too much or too little recycling. Too much or too little means relative to what would occur in a "perfectly" functioning economy, defined as one with a competitive price system, no externalities which are uncorrected by policy, no uncertainity left uninsured against, no distortions of prices by subsidies or taxes, and one which has an "acceptable" income distribution. Although in principle one could conclude that imperfections could cause too much recycling, almost everyone agrees that the cumulative effect of the existing imperfections in this country cause too little. So from now on I'll always refer to "too little," or "insufficient," or "sub-optimal" recycling of paper.

Precisely what is meant by "too little" is that some other allocation of resources, with more recycling and less of some other good(s), would be superior. Supreior means that the value of "national income," appropriately defined, would increase and that the new distribution of income would be no worse than the original one. Those persons who gain by the change would gain more than the losers lose, in the sense that the gainers could compensate the losers, leaving them unharmed, and still have gains left over. Also, we assume that in the new situation, a reversal would not allow gainers to compensate losers. In technical parlance, such a change in allocation is said to meet the Kaldor-Hicks and the Scitovsky criteria (13,17-19,22,27,38).

In most of the paper, I am going to assume that the distribution of income does not change with the reallocation enough to concern us. In other words, I assume we can ignore the distributional changes and make a judgement solely on the sign--positive or negative--of the change in national income. I shall make a few remarks about distribution later. In this kind of analysis, national income must be defined broadly to include the value of all goods and services and activities (including leisure) which enter directly into consumers' utility functions with the values determined by willingness to pay, regardless of whether there are any market trades in the goods or activities--some of the values must be imputed, in other words. Environmental quality must definitely be included. Obviously, this measure of national income is much broader than "GNP."

The value of national income will be at a maximum if there are no imperfections in the economy. The proof of this is a standard result in welfare economics, and will not be repeated here. In this case the amount of recycling is just right, or "optimal." Note that one cannot say there is too little recycling unless one can point to a particular imperfection: one must be able to pair up a misallocation with an imperfection. Also, one must always be able to pair it with a misallocation of the "opposite" kind, that is, if there is too little recycling there must be too much of something else. If one is to argue there is too little recycling, one must find something else such that national income would be increased if recycling were increased and the other thing decreased.

It is generally agreed that several imperfections cause too little recycling and too much use of virgin materials; it is also generally agreed that the excess production from virgin materials also causes a sub-optimal amount of environmental quality and an excess amount of use of primary energy materials. Thus, the chief resource allocation effects are too little recycling and environmental quality, and too much use of virgin materials and energy. Some imperfections also cause other misallocations, in addition to these.

For simplicity, from now on I shall refer to paper produced from virgin material, and the associated production process, as V, and the paper produced from recycled paper as well as the production process and the required recycling activities, as R.

SOME PERSPECTIVE

Before reviewing the imperfections, we must gain some perspective. Increasing the use of recycled paper although offering some marginal improvements in overall resource allocation, has an inherently tough road to hoe. We must not expect dramatic increases, certainly not quickly, even if we eliminate of offset all the imperfections, which we can't do anyway. The research on the imperfections and their effects has made that quite clear. The supply and demand of waste paper have often been shown to be inelastic, which means that either an increase in price to suppliers, or a decrease in price to users, alone, will not expand the market much (1,2,9,10, 12,34,35). And a shift in either demand of supply will cause large price changes which curb the responses from the other side of the market. What seems to be required is a simultaneous shift in both supply and demand functions, so that quantity can be increased without much change in price. This is not out of the question, but opportunities, especially ones soundly based in welfare economics, for doing this quickly seem very limited. The longer-run picture is very clouded, and much of the research done so far has not dealt with it well.

It must be remembered that the U.S., like some other countries which don't recycle much (43), has a large and low cost virgin pulp supply. Recycling is much more labor intensive than virgin production, both in the paper production process and in the waste paper handling itself. The increasing relative price of labor, common to all advanced economies, inhibits recycling therefore. Most of the paper not already recycled is in the "post consumer waste" category, where labor costs and household resistance are high. There are technical limits to the amount of recycled paper which can be substituted for virgin pulp in many grades of paper, and not all of these are traceable to consumer ignorance or purchasing agent biases. Recycling is traditionally more important in some grades of paper than others, but the future growth rates in those grades are forecast to be lower than for the other grades (15). The differential growth rates by grade could swamp modest increases in the recycling rates for each grade. (Arithmetically, of course, one could conceive of the recycling percentage rising in every single grade, but the recycling percentage rate for the whole economy falling!) The bulk of existing paper production capacity is designed exclusively or predominately for virgin pulp, including being located near virgin supplies and far from waste paper supplies; it will take a long time for investment decisions at the margin to change the nature of the capacity and its location to use more waste paper. Some regional considerations are also important. The supply of waste paper is especially abundant in regions of the country (Northeast, Midwest) which are now growing more slowly that other regions (wouth, West), which normally rely more on virgin pulp and which are less urbanized, making the supply of waste paper more costly. And the recent faster growth in nonmetropolitan, less urbanized regions of the country (the "rural renaissance") also seems to work against increases in the use of waste paper.

MARKET IMPERFECTIONS

Without pretending to draw up an absolutely exhaustive list, I thing the main imperfections are as follows:

A. Differential pollution in V and R (V=virgin, R=recycle). It is apparent that in most locations, the potentially damaging "residuals" per unit of output, from V are potentially more damaging than those from R. The situation is complicated by the fact that both V and R produce harmful residuals, in different proportions; R definitely produces more of some harmful residuals than V (7-9,36,43, 46), and in some locations the potential damages are probably greater. The literature on residuals does not disaggregate by location very much, leaving a great deal of useful research to be done on specific locations which might be affected by broad national policies. The de-inking necessary to produce higher grades is especially singled out as generating more solid wastes and waterborne suspended solids (43). Bower presented a great deal of data on the residuals trade-offs involved in choosing a process, specification of product, and raw material in the production of paper (7,8). For example, in the production of tissue, one can technically use up to 100% waste paper in a draft (sulfate) process (brightness 25GEB, waste paper No. 1 mixed). As opposed to 100% virgin pulp, 100% waste paper would produce a 50% increase in SO_2 (the SO_2 would be 0 if sulfur-free fuel oil were the energy source, but in Bower's model 1% sulfur fuel oil is assumed, and with that the total SO_2 actually rises); a big decrease in reduced sulfate compounds (hydrogen sulfide and organic sulfides) and in particulates and in inorganic solid residuals; an increase in organic solid residuals; and a nearly 50-fold increase in suspended inorganic solids. But the increases and decreases are quite different if one considers other processes, other brightness specifications, and other kinds of waste paper. It is very hard to generalize on specific residuals (8). It would be even harder to generalize on the damages caused by discharge into the specific environmental media, with varying assimilative capacities, in specific locations. And even Bower's careful work has been criticized for not recognizing the variations in process specifications from plant to plant, due to varying engineering and management practice and skill, and age of capital equipment (MacAvoy (8).

However, as I have said, there is a presumption that in the typical location V produces more harmful pollution (36, which has an extensive list of references; 46; for a more reserved conclusion, see 31,43). The case is strengthened if one adds the environmental damage in forestry (14) to the paper manufacturing effects. Now, if society does not take steps to prevent the damages, the damage costs will be external to producers; the market prices of V and R will both be below their true social costs, but the price for V will diverge more. Thus, paper producers will be induced to use more V and less R than is optimal. However, one must recognize that public policy is moving gradually toward controlling pollution, which presumably is reducing the difference in the price of V relative to R.

B. Discriminating taxation in favor of V. The chief culprit here is the capital gains treatment of profit from cutting of standing timber for paper production, and also in some cases a lower property tax rate on timber reserves than on durable equipment, and some minor advantages of expensing capital expenditures (1,3,47). The long-run effect of the tax advantages is to lower the cost of virgin paper production, and this seems to be shifted forward on to buyers, thus expanding the use of V above what is would be in an optimum allocation.

However, it appears the effect on the price of V is rather small. Coupled with the usual estimates of low demand elasticity for V, and of low cross elasticity between V and R, it appears the effect on the relative quantities of V and R is quite small, probably well under one per cent. Anderson *et al.* estimated that the effects on the price of virgin paper was 4.2%, even under favorable assumptions, and that the most likely effect was actually only about 1% (1). An earlier report for EPA suggested the effect varied a lot by type of paper, and could be as high as 2% for linerboard, corrugating medium, and printing and writing paper; the report also indicated that the tax effect on the price could be a large proportion of the total difference in production costs of V and R; for example, the tax effect was estimated as about 70% of the total differential for linerboard and corrugating medium, 60% for one kind of combination boxboard, and only 26% for printing and writing paper (47). But even such sizeable numbers may imply very little effect on relative quantities of V and R, except possible there could be sizeable effects in the very long run. As indicated earlier, we really can't say what would happen if various imperfections were removed and we waited a long time to measure all effects.

C. High degree of uncertainity in returns to capital invested in recycling operations and production of paper from recycled material. This is due to the extreme price fluctuations in the price of waste paper (2,3,9,10,10a,35,43-44). The fluctuation is one of output prices for firms, households, and organizations engaged in collecting and selling waste paper; the uncertainty in the rewards to their effort inhibits long-run capital investment, organizational effort, development of experience and routines, and the making of long-term commitments to supply waste paper. It should be clear that uncertainty affects not only business firms, but also households and non-profit organizations whose volunteer has usually been a vital input into waste paper supply. In times of high prices, organizations have developed networks of households who are willing to separate out newspapers and other forms of waste paper, only to have no market for the paper a few months when prices fell so drastically.

This same fluctuation is one of *input* prices to paper mills which rely on waste paper as a raw material. Waste paper prices fluctuate much more than paper product prices, so the profit margins of such mills also fluctuate a great deal. There are standard economic arguments on why such uncertainty, even though it sometimes raises profits and sometimes lowers them, is less conducive to long-term investment and long-term contracts than a *stable* profit which is equal (or even lower) to the *average* of the fluctuating profit levels.

Unlike in the effects of pollution control and tax advantages, we do not have estimates of just how much this uncertainty inhibits investment. Our models for the estimating effects of uncertainty on profit, and on investment, are not as well developed as the industrial process and competitive market models used in the other two areas. Nor do we have the systematic data on the attitudes of entrepreneurs and managers and their opportunities for reducing uncertainty through diversification, holding of inventories, etc. A waste paper dealer might diversify by participating in more than one secondary material market; when paper prices are up, perhaps scrap prices are down, etc. To some extent households and non-profit organizations might do the same. It would appear that paper producers, who buy waste paper as an input, are better able to hold inventories as buffer stocks, but it is hard to see them diversifying into the completely different end-product industries which use other secondary materials, e.g., metals.

Fluctuation in waste paper prices has been attributed to the large shifts in inelastic demand curves along very inelastic supply curves. The large shifts are partly due to the nature of demand for products using waste paper (e.g., construction paper, insulating materials) and the oligopolistic nature of the paper products industry, which means that fluctuations in demand are coped with predominately by output fluctuations rather than (product)price fluctuations. Waste paper is often the residual or marginal source of input supply, and demands for it fluctuate much more than demands for the virgin pulp input; this *accentuates* the instability in paper *output.* Paper firms pay large prices for marginal inputs in times of high demand for their products, because the extreme capital intensity and the vertical integration of most firms puts a premium on keeping enough inputs flowing to maintain a mill in operation.

D. Implicit subsidization of disposal of waste paper. In many locations, *household* consumers of paper do not pay the full monetary cost of collecting and disposing of the paper after use. They do not pay market prices for municipal solid waste "management," but rather it is financed out of general property or other municipal taxes which do not vary as the household's demands on the system, or the costs imposed on it, vary. In addition, even the businesses, in most locations, and the households, in some, who do pay user charges for solid waste management may not be required to pay the full social cost of collection and disposal, because there are some externalities, chiefly in disposal, not reflected in charges. For both these reasons, solid waste disposal is subsidized. As disposal is a complementary good to V or a substitute for R, the implicit subsidization helps overexpand V and restrict R. The subsidization reduces the incentives for recycling, by preventing some of the social cost savings from recycling from flowing to the firms and individuals who recycle: if nothing need be paid to dispose of waste, nothing is saved by recycling instead of disposing.

This is a dominant theme in the literature on recycling and why it is insufficient. The argument runs through almost every bit of general economic analysis of recycling and is used in almost every policy proposal for encouraging it. The precise quantitative significance of it is less certain. Certainly the quantitative significance must vary greatly from place to place and from one type of paper product to another. The geographical variation is due to the variation in the correct disposal price which would be imposed if the imperfection were eliminated, and also due to the variation in the cost at which recycling can be substituted for disposal (this depends on the density of settlement, the network of supply and the accessibility to markets, etc.). The variation from product to product is due to similar reasons: the disposal cost and the ease of recycling varies.

The increase in price of disposal would undoubtedly increase the effective "price" of R (market price of waste paper plus the disposal charge saved) sufficiently, in *many locations*, to make households, firms and organizations increase the supply of R. This increase in supply would lower the market price of R to users, stimulating some additional use. In a new equilibrium, the effective "price" to households, etc. would be higher; the market price to users would be lower; the difference is the disposal cost. However again we have the problem that inelastic supply and demand would probably severely limit the increase in quantity used.

As so often in recycling, we find we should expect considerable spatial variation in effects. Indeed, a major conclusion from the research in the field, although one not always made by authors, is that effective research must move beyond generalities for all paper, and for the nation as a whole, and on to a careful examination of individual regional and metropolitan markets. In the case of a disposal fee system, we would expect the major increases in recycling, if anywhere, to come in the large, densely settled urban areas of the Northeast and Midwest. Why? Because they are the regions where few cities already charge user charges, where many cities have a shortage of land for sanitary landfill, and where the density of population and the presence of paper mills relying on waste paper. However, they are also regions where a relatively large proportion of paper is already recycled, which may limit the marginal response.

But there should be very great spatial variation, even within broad regions. It is imperative, in order to forecast more accurately the effects on recycling of eliminating or reducing the imperfection in disposal pricing, to do more disaggregated--regionally--analysis.

A rather important factor in the implicit subsidization of disposal is that many users of paper already pay a user charge; these are the large business and commercial and institutional users, who routinely must pay for collection and disposal even in cities where households do not. This point must be remembered when considering policies to eliminate or offset the imperfection; for example, one cannot deduce from the existence of subsidies for disposal to households that a general subsidy for recycling, extended to businesses as well as households, is justified. Or, at least, the subsidy should not be at the same rate for businesses as for households (3,36).

E. Biases against use of R in large vertically integrated paper product firms. Suspicion of such biases is based on a variety of hear-say evidence but also on Cardin's careful study (10a). The point here is not simply that the large paper firms do not use much R in their operations, nor that their location and technology makes it difficult to use much R. That behavior could be very consistent with sound business practice and cost minimization, especially in the short run, when the nature (including location) of capacity is fixed. Rather, what is suspected is that some managers actually sacrifice profits in order "discriminate" against R, and in order to indulge their own prejudices or to avoid having to make careful calculations or take moderate risks.

Contributing to such biases are said to be the lack of experience with R, the geographical isolation of environmentally damaging production facilities from the offices of managers, the long-standing organizational structure of the firms, and social differences between the typical manager and the typical entrepreneur in the recycling business.

There has not been enough research yet to enable the impartial observer to reach a sound conclusion. In particular, we do not know just how strong the biases are; we don't know how to quantify them, in the sense of knowing what price differential between V and R is sufficient to erode them. It is difficult to separate biases from normal risk aversion, which also explains reluctance to use R.

If the biases exist, they should be most easily detected in the investment decision by integrated firms. What technologies, what capital intensities, what locations are chosen when capacity is expanded? Research on the investment decisions of the firms has not been plentiful; it has been slighted relative to studies of price fluctuations in waste paper markets, to studies of costs, returns, and pollution in pro forma, "ideal process" hypothetical case studies.

But it is in the investment decision that managers of these firms do in fact have real choices, and it is in data on those choices that we should find evidence of the trade-offs open to them, as well as evidence on how they perceive or mis-perceive the trade-offs.

As a final note on this, we note that Cardin's work was squarely in a modern tradition of organizational and behavioral research on the large frim (see, as a general example, the work of Williamson (51)). Considerable empirical and case-study research has already been done, for example, on the effects of the basic organizational structure of the firm on its production and investment decisions and on its performance. That research can be built up for additional work on the paper industry.

Imperfections Which Go the Other Way. We would be remiss if we failed to recognize some imperfections which have the opposite effect from the ones we have reviewed so far. One is the failure of capital used by municipal governments to be required to return, in monetary and/or imputed benefits, its full social cost. The chief reason is the Federal income tax exemption of municipal bond interest; that allows the budgetary cost of municipal capital to be below the social opportunity cost. In addition, we certainly should have even less faith in municipal managers to be "efficient" than we have in paper industry managers. This could bias society in favor of recycling, *ceteris paribus*; while it probably has limited relevance now, it is something to worry about if we introduce a wide-scale program to subsidize municipal recycling, especially if we wanted to subsidize municipal *capital* facilities in recycling. Indeed, recognition of this point makes us unenthusiastic about subsidies of that kind. However, so far the bias probably operates significantly only in municipal "resource recovery" facilities, in which paper is generally recovered as energy or very low grade fiber, rather than in the forms we are discussing here.

Another possible imperfection is monopsony power in waste paper markets. We have come to think of them as very competitive, in sharp distinction to the oligopolistic markets for paper products. But it is possible that some paper mills using R, and some waste paper dealers, have considerable buying power, especially in small city markets. Recently a major recycling paper mill executive commented that in times of shortages, some dealers tried hard not to raise the prices they offered to the public and to maximize the spread between their buying price (paid to the public) and their selling price (received from recycling paper mills). He pointed out that the dealers' refusal to raise "door" prices (paid to the public) denied the supply effect that higher prices would have had (44). To the trained economist, this sounds rather like monopsony. There has been surprisingly little (none?) research on this possibility, perhaps just because we have been lulled into seeing a too-sharp distinction between the structure of the paper products industry and the waste paper industry.

A NOTE ON CONSUMER PREFERENCES

In all the preceding analysis, there are several important assumptions about consumer preferences and individual welfare. First, preferences are given and unchanging; in particular they are not affected by any policies. Second, individual welfare depends only on one's own consumption, and not on any others. Third, recycling *per se* is not valued directly by individuals. If we abandon one or more of these assumptions, we add some other arguments for recycling. While this is not a step normally taken by economists, even those most fervently in favor of recycling, there are some definite possibilities we should explore. They call for research on attitudes and taste formation, rather than the usual kind of economic research.

One might simply argue that recycling is a "merit good," and that government should provide it even though individuals don't want it, or don't want it now. Maybe their tastes will change with experience, and they will value it directly or because it is a "husbanding" of scarce resources.

Another approach, only a bit less speculative, is to assume there are interdependencies in consumption, so that one person's consumption pattern directly affects another's welfare. I have in mind not interdependence due to physical impacts, as in pollution or congestion; that is already covered under the rebric of externalities. Rather, I have in mind psychological interdependence--one person simply cares what another does. This is not usually allowed for in the usual economic analysis of recycling, or in anything else, for that matter--economists have as yet paid little attention to such interdependencies. But in principle, if they exist and private markets cannot take account of them, we have an additional imperfection which prevents markets from achieving results consistent with consumer sovereignty. The imperfection would exist, of course, only if high transactions costs inhibited individuals from effectively offering financial inducements to each other to engage in consumption which was mutually pleasing. Government could then provide economies in transactions.

This is still somewhat speculative. I know of no research on the argument which is soundly based on theory and which offers testable hypotheses. However, there are some recent developments in economic theory of interest. One example is Thurow's notion of "individual societal preferences," according to which individuals care about others' consumption of basic goods like education, medical care, and justice (41). Person A may feel pleased that Person B recycles, not because he lives or works near B and is affected physically by it, but simply because he is pleased that B "husbands" scarce resources (this example is mine, not Thurow's).

Sen (39,40) has also applied the notion of consumption interdependencies (or consumption externalities) to justify collective acction, in this case national saving. Although the whole subject is a bit new, there is in principle nothing objectionable about it. In a welfare economics fundamentally based on the notion of individual welfare, we should accept that individuals' welfare can depend not only on their consumption but on others consumption as well. In practice, of course, it is a social decision on just what interdepencencies to recognize in public policy. We might rule out some as not socially acceptable; for example, we might rule out mere envy, or ones which imply racial or sexual discrimination, or a disutility caused by a neighbor's painting his house salmon pink.

In order for this to have any legitimacy in recycling, I think we would have to show the feelings are widespread. Whether or not they are is highly debatable, but research is needed. It is certainly quite clear that a lot of people do not like to bundle up old newspapers, and care not a whit whether you or I do either. They are not bad people; they may have other attitudes which make them care deeply whether you or I have good housing or medical care, or are provided basic justice, but they simply don't care about recycling. Some of them may care about "husbanding" non-renewable resources, but may not care about paper because it is a renewable resource; that would be quite legitimate.

To conclude this review of imperfections, we note that the approach to the problem leads to proposed policies and a particular view of them. There are two sets of policies: one to reduce or end the imperfections; the other is to introduce new imperfections, which perhaps paradoxically, increase the national income by offsetting the other ones. It is generally true that the best approach, which would increase national income the most, is to eliminate the original imperfections. Unfortunately, that is strictly true only if all the imperfections can be eliminated. If a policy is constrained--politically or legally--to tolerate the continued existence of one or more imperfections, then it may turn out that adding a new, offsetting one, is the "second-best" policy--it will increase national income somewhat, but not as much as the first-best policy. Clearly, policymakers certainly cannot eliminate all imperfections in society which affect recycling in one way or another. They must proceed in a more piecemeal fashon. Therefore, a second-best analysis is required routinely. It is useful, therefore, to review second-best theory and attempt some conclusions from it.

SECOND-BEST THEORY

A "second-best" problem is one in which there are imperfections, and a policy is to eliminate some of them, but not all. A constraint on the policy is that some imperfections remain. For example, we may have pollution externalities in the production of A, but we also have a monopoly in A. Our "first-best" policy is both to correct for externalities (as with an effluent tax, or the optimal amount of regualation) and to eliminate the monopoly. But suppose the monopoly must remain--it is a political fact of life, or a legal requirement, or whatever. If so, the "second-best" analysis is required to determine just what should be done to reduce the externalities. In general, it is not always the case that a policy called for by first-best analysis is called for in second-best. In our example, a first-best policy includes effluent taxation, the rate set at the marginal damages. In a second-best case, it is easy to see that it is not necessarily good to tax the firm's effluent, even at the rate which would be optimal in the first-best case. The reason is that the monopoly restricts the output of A below the socially optimal level, but the failure to tax the effluent artifically expands the output. A tax on effluent will restrict the output by even more than the monopoly restricts it, so it will accentuate the distortion in resource allocation from the monopoly. We can't know *a priori* whether that is an improvement unless we know just what increase in evironmental quality will occur as an offset to the reduction in output of A. The balance might go either way: the reduction in pollution might be greater than, or less than, enough to offset the loss of output of A. Put another way, in the original situation, the overproduction from the failure to tax effluent might have just offset the underproduction from the monopoly, leaving the output of A about right, (assuming, as always, that the monopoly *had* to remain). This case is discussed in (4). Just how much to tax the effluent, if at all, cannot be determined without knowledge of all the elasticities, the cost functions, and the marginal damage function, and without calculations trading off gains versus losses. The only safe conclusion is that no simple rule can be laid down (4,16,19, 21).

One is not caught helpless, however. Mishan (26,28) has suggested some cases in which certain policies are highly likely to produce increases in national income, and on his analysis we can build applications relevant to recycling policy. Consider the following hypothetical situations, in which we analyze imperfections and policies affecting goods A and B. Assume also that the imperfections and policies affect only A and B, and no other goods, or at least predominately so. This may be the case where A and B are close substitutes for each other, and neither is a close substitute or complement for any other good, in either consumption or production.

Case I. Two imperfections have roughly offsetting effects on A; for example, monopoly and uncorrected pollution in A. This is the example discussed earlier; the monopoly restricts A (and expands B), while the uncorrected pollution expands A (and restricts B), relative to the optimum. The second-best policy would include a tax on effluent and a subsidy to firm A (based on the level of output, and equal, per unit of output, to the difference between marginal cost and marginal revenue at the optimal level of output) (4).

Case II. Imperfections in both A and B, which tend to offset each other. For example, monopoly in A, excise tax in B. The monopoly restricts A, expands B; the excise tax restricts B and expands A. The two may offset each other, leaving the two outputs closer to the optimal levels than if one imperfection were eliminated completely or reduced greatly. This is especially true if A and B are very close substitutes.

Case III. Imperfections in A, which accentuate each other. For example, a subsidy to A and uncorrected pollution in A. Both these artificially expand A and restrict B. Now, eliminating only one of the imperfections would partially reverse things, and would very likely to be a change for the better. In practice, we would still have to be careful about changes resulting in other goods and services, which we have ruled out in these examples.

Case IV. Imperfections in A and B, which accentuate each other. An example is a monopoly in A and a subsidy in B, another would be uncorrectd in pollution in A and an excise tax on B. Here, too, elimination of just one of the imperfections in the pair would very likely improve things.

Now, let us return to Case III, and assume that we cannot eliminate either of the distortions. However, it is likely that we can improve things if we convert the case into something like Case II, by adding a new imperfection which offsets the combined effect of the two in Case III. The two imperfections in A both overexpand A; what is a possible offset is a subsidy to B, which expands it. It will be readily seen that this is analagous to the situation in V and R. In V, we have several imperfections (tax advantages, uncorrected pollution, subsidy through solid waste disposal), all of which move productions of V in the same direction--toward above-optimal amounts--and all of which move production of R in the same direction--toward sub-optimal amounts. A subsidy to R would help offset them.

While the subsidy to R may--probably will--improve welfare, it can be shown that the new imperfection is only a second-best policy, at best. It cannot completely reverse the losses imposed on society by the imperfections in R, as would a first-best policy of eliminating all the imperfections in V. For one thing, introducing a subisdy on a product requires, for budgetary balance, an increase in government taxation somewhere in the economy, and that introduces new imperfections somewhere else, which may create new losses, and which dilute the benefit of offsetting the orignial imperfections in V. The probability of this can be reduced by imposing the new taxes in broad-based way, rather than concentrating them on one or a few goods.

In addition, the subsidy to R will not completely offset the original losses because it will contribute to an expansion of the paper products industry beyond the socially optimal amount. While it corrects for the overuse of virgin material at the expense of recycled material, it also lowers the price of the final product, and stimulates an increase in quantity which has a marginal cost ot the economy greater than the marginal valuation by consumers. This basic point is often missed in economic analyses of recycling, but it is made by Anderson (3).

Figure 1 illustrates some of the simple aspects of subsidy to R. The numbers are hypothetical and are only examples. The diagram refers to paper products; D is the demand curve. There are constant costs; if V is used as a raw material, the marginal cost and price, MC_V and P_V, are both \$100; if R is used, MC_R and P_R are both \$90.

In the initial situation, there are no subsidies, so only R is used and P_R = 90; quantity is 100.

Now, assume a subsidy is given to V, translating to a price advantage of $20 per ton of product; price now falls to P_V , which is $80. Now only V is used, to the total exclusion of R, and quantity rises to 110.

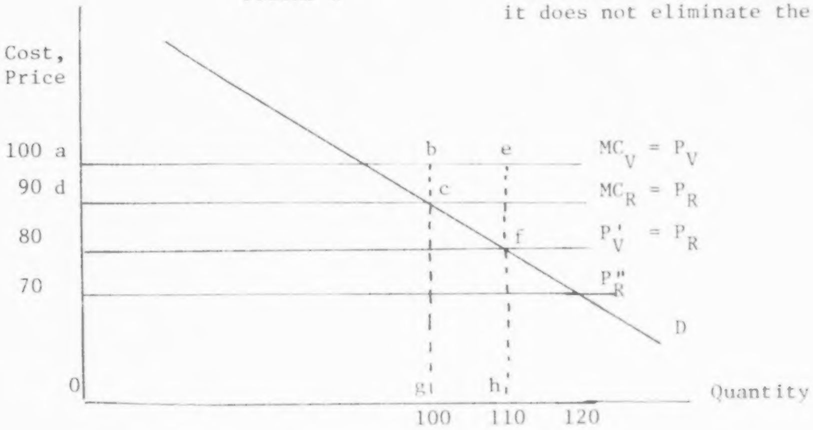
Compared to the original situation, the economy has suffered two kinds of welfare loss. First, a more expensive input has replaced a cheaper one on the original quantity; second, the industry has overexpanded, with the additional output having a marginal cost of $100 but a marginal value to consumers of less than that. The first loss is area abcd, equal to $1000; the second area is bcfe, equal to $150 (this is also bghe, total cost of added output, minus cghf, total value to consumers of added output). Thus, total loss is $1150.

Alternatively, we can derive the $1150 loss as the added cost of producing the total supply of paper, which is Oaeh ($11,000) minus Odcg ($9,000), less the added value to consumers from increasing the total supply of paper, which is gcfh ($850). That is $1,150.

Now, assume a subsidy is introduced on R, translating to a price reduction of $10; price of paper made with R now falls to P'_R = 80, which is equal to P'_V. Assume that because the priced are equal, each gets half the market, which remains at 110. The average cost of paper products is now $95 (average of MC_V = 100 and MC_R = 90), so the total costs of producing the paper which is sold is $10,450, an increase of $1,450 from the initial position (P=90, Q=100). The value of the added paper to consumers is only $850, as in the previous case, so the loss is now $600.

If at equal prices, only R was used in the manufacture of paper products, the loss would be almost eliminated, but not quite. The cost on the original quantity (100) would be again 9000 as in the very first situation, so there are no losses from use of higher price input instead of lower price input. However, there is an expansion of the industry of 10 units; they have a marginal cost of $90, or a total of $900, while as we have seen the added value to consumers is only $850. So there is still a loss of $50. Even though the subsidy on R is only enough to bring R to par with V, it does not eliminate the

FIGURE 1



welfare loss due to overexpansion which the original subsidy to V caused.

What would happen if the subsidy to R were made "too large," that is larger than the $10 needed to bring R to exact par with V? Assume the subsidy were mistakenly made $20, lowering price to R to $P^*_R = 70$. The quantity would now rise to 120, and the loss would increase (that is, the loss from the very first position with no subsidies at all). The added cost to the economy would be 20 units of product times $90 per unit (remember the MC_R is $90), or $1800; the value to consumers (area under demand curve) would be only $1600 so the loss would be $200. This illustrates the fact that a subsidy to recycle should be no larger than the amount needed to offset the original imperfection, and even then there will still be a small welfare loss compared to a "first-best" position (the welfare loss in this case will be larger, of course, the greater is the price elasticity of demand).

This whole analysis assumes that the subsidy to R is such that there are no further distortions in the production of paper products due to biased input prices. In particular, the subsidy will have additional welfare losses if it is based on capital used in recycling, rather than on the use of recycled material per se. This possiblility is mentioned becaused subsidies to capital are politically popular, taking the form of construction grants, low-interest loans, etc.

INCOME DISTRIBUTION EFFECTS

I promised earlier to deal with these. I think there are two things to worry about. One is that subsidies should be designed to avoid large windfall gaines to recyclers who would have recycled even without the subsidy. Improperly designed subsidy schemes without marginal incentives will have a rather low increase in recycled paper per dollar of tax revenue used to pay the subsidy; that both has an unfortunate distribution effect and also requires more distortions elsewhere in the economy (due to taxes) per marginal ton of recycling.

The second thing to worry about is the distributional impacts if we eliminate the imperfection due to failure to price solid waste disposal. Frankly, I don't think even these impacts are very important; they are small amounts of money and the disadvantage in vertical equity is partially offset by an increase in horizontal equity resulting from a fairer, cost-based price system. But they may be politically important, and in fact may be one of the most important reasons why we move toward "second-best" policy of subsidizing recycling rather than a first-best policy including solid waste user charges. For extended treatment, see (6a).

CONCLUSIONS FROM PREVIOUS RESEARCH AND RESEARCH AGENDA

The policymaker needs research in order to guide policymaking. But financing research--or doing it in-house--is also a policy. The research on recycling paper must be guided by the need to allocate scarce research funds effieiently. Here I wish to sketch out some suggestions for further research. Again, I shall follow my list of major imperfections affecting recycling paper.

A. Pollution. The relative gap between V and R is presumably being reduced grandually. Eventually, it may be eliminated. If so, the pollution question will become moot, and it is not a wise investment to do detailed research on relative pollution loads in V and R. On the other hand, if the differences are going to persist, we need much more specific research than we have had so far--specific on different locations and the assimilative capacity of the environmental media in them, specific on the differences in enforcement, on the lags in behavioral responses of managers, the effects of varying ages of plants, etc.

B. Taxation. The research we have so far is very good. It indicates that the taxation effects are not very big, in paper. The effects even in the long run, although uncertain in size, will probably not have much present value; the effects will be delayed because the effects on V will be delayed and because the response (in the form of investment) of paper firms to changes in V will be delayed. The payoff to eliminating the tax advantages doesn't seem very big, so the payoff to further research on the subject doesn't either. Another factor is that more research will hardly make a difference in the political decision; the political economy is against the change. Removal of the tax advantages would have a more concentrated negative effect on landowners and paper firms but it would have a diffused positive effect on consumers of paper products in which recycled material could be easily substituted. Many consumers of timber products and of paper products in which a lot of V must be used will of course be hurt.

I may be wrong on the last point. For many years, we didn't feel the oil depletion allowances could be eliminated either, but finally they were. However, it took a profound energy crisis, which we are not likely to see in paper.

C. Solid Waste Disposal. Research on the effects of improper disposal pricing is one of the highest priorities, I think. Fortunately, there is a lot being done, on the effects of a product charge, of moves toward pricing by municipalities, etc.

This kind of research is important for several reasons. First, the effect on the realtive prices of V and R may be very high. For some users, the present system effectively reduces the price of disposal to zero, which is a large change. Second, there seems to me to be a genuine chance that good research will lead to change. I am not too hopeful on the product charge; it seems simply to be too big a jump into uncharted areas of Federal policy. But research on municipal pricing would probably increase the chances of reducing the present implicit subsidy gradually in the long run. I believe that if the effects of municipal pricing are better understood, it will be adopted more widely. Cities will see how limited the effects are on the distribution of income, and will gain experience on pricing methods. Many cities are ready for reassurance that pricing is a legitimate way to resolve mounting solid waste problems, which on account of increasing labor and disposal space costs are becoming more serious. Cities are also useful groupings of people in which to capture the consumption interdependencies I discussed earlier, which may ease the way to introducing charges. Furthermore, it is not the case, as in pollution, that other government policies are already gradually removing the imperfection; there is a move to reduce externalities from open dumps, but they are only a small part of the implicit subsidy.

The recent popular movement ("propulism," it has been called) to reduce property taxes also makes a move to user charges more feasible, so that research on the details of execution and of impact is very valuable.

In addition, there are two genuine contenders for pricing policies: municipal user charges and the national product charge. And of course they compete with recycling subsidies as candidates for adoption. There is still much to be learned about which of these policies is the best.

I would favor increased municipal user charges. There are advantages of efficiency and equity. Charges can be varied from location to location, which should contribute to efficiency and to horizontal equity. They would help educate people to husband scarce resources more carefully and thus improve the internalization of consumption interdependencies. The product charge, on the other hand, seems to rigid and too remote from individuals to have the same advantages. It cannot allow for wide variations in social cost of disposal, and cannot easily allow for the fact that many business and commercial users already pay user charges; levying the product charge on paper used by them would indroduce a new imperfection which would not offset any existing ones. It would have some of the same adverse effects on vertical equity (income distribution) as municipal charges, but would not have the advantages of increasing horizontal equity--which requires individuals imposing different costs on the solid waste managment system to pay different charges. The product charge would apparently give a rebate to users of recycled material, which is a help, but it would still levy the same charge on all persons who disposed of waste, no matter how the social cost of handling their waste varied.

A recycling subsidy is less desirable than municipal charges, because of the minor distorting effect described above, because any practical scheme would probably dispense windfall gains to a few even as it collected taxes from the general public, and because in practice it would be hard to withhold it from users who already pay user charges for solid waste disposal. As we saw earlier, the subsidy properly should not be available to persons and firms who already have the appropriate incentives for recycling.

Many of these things are controversial, and the effects--on distribution and on degree of recycling and on solid waste disposal costs--are speculative. But this is probably the most important single imperfection in our system, and the times are ripe for change, so resolving these questions is the highest priority in research.

D. *Uncertainty in Waste Paper Markets*. The theoretical effect of uncertainty, caused primarily by the marked fluctuations (and unpredictability of fluctuations) in the market price, are well known. One must assume they might be very significant. But what is surprising is how little research has been done on the quantitive significance. Most of the literature so far merely repeats, with some embellishment, the standard theory on uncertainty and investment, and moves from it to a conclusion that some public policy is needed to offset the uncertainty. In some cases, there is a too-easy jump to the conclusion that *subsidies* to recycling are needed.

We need to move beyond this stage and try to quantify the amount of risk aversion. This may require far more than routine econometric analysis of existing data, for we don't have data for periods when the risk and uncertainty were lower. We can hardly analyze the effects of reducing uncertainty by analyzing data from a period when the uncertainty has not been reduced.

Perhaps here, as in the case of research on solid waste user charges as well, we need some "social experiments," similar to the ones on the negative income tax, housing allowances, etc. At any rate, we need to probe the attitudes of participants in recycling processes, not merely business firms but also individual households and non-profit organizations. Particular attention should be paid to investment decisions of the large integrated paper products firms, for research on that also helps us understand the degree of "biases" on their part, which is another important research subject. And, of course, the attitudes of municipal officials must be studied. They will be making some of the most important decisions on recycling, including investment decisions. Are they unusually averse to risk, even though they are not employed by profit-making enterprises? Does it make a difference how recycling is organized in municipal government, that is, does it make a difference whether it is part of the regular public works function or a separate, somewhat autonomous and free-standing public corporation? How does the risk from recycling correlate with other risks in municipal government--what is the "portfolio effect" of adding recycling to the municipal managers' package of responsibilities, which has various risks of financial and political kinds? One can think of many other questions in this area which have not been studied much, but which seem important to answer if we are to evaluate recycling policies.

Another example is the effects of a buffer stock stabilization scheme, which might be operated by a local or higher level government. Even if municipal officials don't try to earn profits in such a scheme, the budget surpluses or deficits that result will certainly affect their attitudes and the attitudes of voters. Yet it is hard to generalize, as Pearce has pointed out (32,43), on whether a buffer stock will make surpluses or deficits, even if it is clear that it will or will not produce social benefits.

Even if we learn more about the nature of uncertainty and risk aversion, the appropriate policies are not completely clear. It is not at all clear, for example, that an outright subsidy is appropriate. This point comes out of the theoretical literature on cost-benefit analysis and public investment theory (3a). A subsidy is not appropriate if it does nothing to reduce the real social cost of risk and uncertainty, but merely redistributes it. This seems to be relevant: the risk and uncertainty of excessive price fluctuations in waste paper is not only a private risk but is a social risk. The basic structure of markets produces uncertainty for the society as a whole; while a subsidy might reduce the part of it which rests on business firms in the industry, it would not reduce the total risk. The more appropriate policy would seem to provide insurance of some kind, so that spreading the risks over many firms would reduce the perceived cost to each one. Even if the fluctuations are not reduced per se, an insurance scheme could reduce their real cost to firms by eliminating the possibility of concentrated losses to any one firm. The same sort of thing might be accomplished by makeing public investments in recycling facilities, and spreading the costs over so many taxpayers that there is no real cost to any of them (4a). Or, a private insurance scheme in the form of organized futures markets might be set up (2). All of these possibilities require further study; a high research priority is thus how to translate the theoretical conclusion on the effects of risk on investment into practical policies.

E. Biases on Part of Paper Firm Firm Managers. As said earlier, we are still unsure whether the biases reported by Cardin (10a) and others are really there, and how important they are. We don't know how separate they are from normal risk aversion; that is why work on investment decisions is so important, for it will shed light both on this subject and on the subject covered just above. We don't know how long the biases would stand up before an aggressive policy, to subsidize recycling or to rationalize solid waste disposal pricing.

It is important to know more about these things, not because those who make policy on recycling can have any hope of "reforming" the industry, even assuming for the sake of argument that it needs reforming, but simply because the effectiveness of other policies depends crucially on the response of the industry. The degree of response, the speed of response, the spatial variation in response--all of these are important. If we were to find that there are biases in the industry, recycling policy presumably must accept their continued existence at least for awhile. Policy must be shaped to have an effective impact under the constraint of the biases; here we have still another example of second-best policy and framing it intelligently requires a lot of second-best analysis.

Let me make a final point. Much of our previous research, useful as it has been--has focused on one imperfection at a time. We need to move toward research in a wider context, analyzing the removal of more than one imperfection or offsetting more than one at the same time. What, for example, is likely to be the effect of simultaneously changing pollution controls in paper manufacturing and introducing solid waste disposal charges in municipalities?

Of simultaneously introducing charges and more subsidies for demonstration, education, and "experiment" projects? Of simultaneously introducing a futures market in waste paper and user charges? Our research has provided very notable insights into effects of individual imperfections, and has made fairly clear the direction--if not necessarily the magnitude--of effects on recycling in each case. We still have a way to go in exploring the effects of imperfections, and policies, considered jointly.

ACKNOWLEDGEMENTS

Some of the research behind this paper was performed under contract with the Solid and Hazardous Waste Research Division, Municipal Environmental Research Laboratory, U.S. Environmental Protection Agency. I am especially grateful to Oscal Albrecht, Haynes Goddard, Fred Smith, Robert C. Anderson, and Ralph Bradburd for comments at various stages of the work. I am solely responsible for any errors of fact or interpretation.

REFERENCES

1. Anderson, Robert C. and Spiegelman, Impact of the Federal Tax Code on Resource Recovery, U.S. E.P.A., Washington, 1976 (NTIS)

2. Anderson, Robert C. and Dower, Roger, An Analysis of Scrap Futures Markets for Stimulating Resource Recovery, U.S. E.P.A., Cincinnati, 1978 (NTIS)

3. Anderson, Robert C., "Recycling Policy: Basic Economic Issues," in Pearch and Walter (33).

3a. Arrow, Kenneth and Lind, R., "Uncertainty and the Evaluation of Public Investment Decisions," American Economic Review, 60: 364-78 (1970)

4. Baumol, William and Oates, Wallace, The Theory of Environmental Policy, Prentice-Hall, Englewood Cliffs, N.J., 1975, pp. 71-3, relying partly on Buchanan, James, "External Diseconomies,Corrective Taxes, and Market Structure," American Economic Review, 59:174-7 (1969).

5. Bingham, Tayler, "Allocative and Distributive Effects of a Disposal Charge on Product Packaging," in Pearce and Walter (33).

6. Bingham, Tayler, et al., An Evaluation of the Effectiveness and Costs of Regulatory and Fiscal Policy Instruments on Product Packaging, Research Triangle Institute, Research Triangle Park, N.C., 1974.

7. Bower, Blair et al., "Residuals Management in the Pulp and Paper Industry,: Natural Resources Journal, 11:605-23 (1972).

8. Bower, Blair, "Studies of Residuals Management in Industry," pp. 275-320, and MacAvory, Paul, "Comment,"" pp. 321-4, in Mills, Edwin, ed., Economic Analysis of Environmental Problems, Columbia University Press for National Bureau of Economic Research, New York, 1975.

9. Bower, Blair, "Economic Dimensions of Waste Recycling and Re-use," in Pearce and Walter (33).

10. Butlin, John, "The Prices of Secondary Materials and Recycling Effort," in Pearce and Walter (33).

10a. Cardin, Frederick, Secondary Fiber Recovery Incentive Analysis, U.S. E.P.A., Washington, 1974.

11. Darby, Michael, "Paper Recycling and the Stock of Trees," Journal of Political Economy, 81:1253-5 (1973).

12. Deadman, D., "Modelling the U.K. Waste Paper Market, "Resource Recovery and Conservation, 3: 237-48 (1978).

13. Dorfman, Robert and Dorfman, Nancy, "Introduction," in Dorfman and Dorfman, eds., Economics of the Environment, W.W. Norton, New York, 1972.

14. Environmental Studies Board, National Academy of Sciences/ National Academy of Engineering, Man, Materials, and Environment, MIT Press, Cambridge, 1973

15. Franklin, William et al., Paper Recycling: The Art of the Possible, 1970-1985, Solid Waste Council of the Paper Industry, Kansas City, Mo., 1973.

16. Henderson, James and Quandt, Richard, Microeconomic Theory, second ed., McGraw-Hill, New York, 1971.

17. Hicks, James, "The Foundations of Welfare Economics, Economic Journal, 1939, p. 696.

18. Kaldor, Nicholas, "Welfare Propositions in Economics," Economic Journal, 1939, p. 549.

19. Layard, Richard, and Walter, Alan, Microeconomic Theory, McGraw-Hill, New York, 1978.

20. Lingle, Stephen, Recycled Materials Markets: February 1975, U.S. E.P.A., Cincinnati, 1975.

21. Lipsey, Richard and Lancaster, Kelvin, "The General Theory of Second Best," Review of Economic Studies, 24: 11-32 (1956).

22. Little, Ian, A Critique of Wel-Economics, second ed., Clarendon Press, Oxford, 1957

23. Miedema, Allen, Market and Net Welfare Effects of Secondary Materials-Biased Input Market Distortions, Research Triangle Institute, Research Triangle Park, N.C., 1975.

24. Miedema, Allen, et al., The Case for Virgin Material Charges: A Theoretical and Empirical Evaluation in the Paper Industry, Research Triangle Institute, Research Triangle Park, N.C., 1976

25. Mills, Edwin, The Economics of Environmental Quality, W.W. Norton, New York, 1978.

26. Mishan, Ezra, "Second Thoughts on Second Best," Oxford Economic Papers, N.S. 14: 205-17 (1962).

27. Mishan, Ezra, "A Survey of Welfare Economics," Economic Journal, 70:197-256 (1960).

28. Mishan, Ezra, Cost-Benefit Analysis, second ed., Praeger, New York, 1976.

29. Nathan, Thomas, "Mining Urban Ore," EPA Journal, February 1979, 24-6, 40.

30. Page, Talbot, Conservation and Economic Efficiency, Johns Hopkins U.P. for Resources for the Future, Baltimore, 1977.

31. Pearce, David, Environmental Economics, Longman, London, 1976.

32. Pearch, David and Grace, R., "Stabilising Secondary Materials Markets: The Case of Waste Paper," Resources Policy, June 1976.

33. Pearce, David and Walter, Ingo, eds, Resource Conservation: Social and Economic Dimensions of Recycling, New York U.P., New York, 1977.

34. Plaut, Thomas, An Econometric Analysis of Regional Wastepaper Markets, Regional Science Research Institute, Philadelphia 1978 (Discussion Paper No. 104).

35. Plaut, Thomas and Steiker, Gene, Characteristics of Wastepaper Markets ..., Regional Science Research Institute, Philadelphia, 1978 (Discussion Paper No. 103).

36. Purcell, A., and Smith, F., "Energy and Environmental Impacts of Materials Alternatives," Resource Recovery and Conservation, 2: 93-102 (1976).

37. Resource Conservation Committee, Transcript of Hearing on Solid Waste Product Charge Issue, Nov. 17, 1977, U.S.E.P.A., Washington.

38. Scitovsky, Tibor, "A Note on Welfare Propositions in Economics," Review of Economic Studies, 9: 77 (1941).

39. Sen, A.K., "On Optimizing the Rate of Saving," Economic Journal, 71:479-96 (1961).

40. Sen, A.K., "Isolation, Assurance and the Social Rate of Discount," Quarterly Journal of Economics, 81:112-24 (1967).

***

41. Thurow, Lester, "Cash versus In-Kind Transfers," American Economic Review, May 1974, 190-95 (vol. 64, No. 2). ***

42. Tillman, D., "Comparison of Two Government Reports as to their Approaches to Recycling," Resource Recovery and Conservation, 2: 361-4 (1977).

43. Turner, R., Grace, R., and Pearce, D., "The Economics of Waste Paper Recycling," in Pearce and Walter (33).

44. U.S. Citizens Advisory Committee on Environmental Quality, A New Look at Recycling, U.S. G.P.O., 1976.

45. U.S. Council on Environmental Quality, Resource Recovery: The State of Technology, Washington, 1973

46-49. U.S. Environmental Protection Agency, First, Second, Third, Fourth (respectively) Reports to Congress on Resource Recovery and Source Reduction, U.S. G.P.O., Washington, 1974, 1975, 1976, and 1977.

50. Whitcomb, David, Externalities and Welfare, Columbia U. P., New York, 1972.

51. Williamson, Oliver, "Managerial Discretion, Organization Form, and the Multi-Division Hypothesis," in Robin Marris and D. Wood, eds., The Corporate Economy, Harvard U.P., Cambridge, 1971.

52. Wisecarver, Daniel, "The Social Costs of Input-Market Distortions," American Economic Review, 64: 359-72 (1974).

***See also McPherson, Michael, "On the Theory of Endogenous Preference Change," unpublished paper, Williams College, 1978.

ECONOMIC AND INSTITUTIONAL IMPEDIMENTS TO CONSERVATION AND RECYCLING

Robert C. Anderson
Environmental Law Institute
1346 Connecticut Ave., N.W.
Washington, D.C. 20036

ABSTRACT

For a variety of reasons it has been suggested that the United States should act to conserve resources and increase the domestic rate of resource recovery. These suggestions are buttressed by evidence that in some instances the forces of the free market do not provide for socially desirable levels of conservation and recycling.

The critical issues for public policy are (1) whether the government should intervene in resource markets and (2) if so, what form the intervention should take. Examination of these points reveals that existing research and information is not yet sufficient to provide a conclusive recommendation. One cannot on the basis of existing information rule out the possibility that the best policy is merely to continue the status quo.

INTRODUCTION

A widespread perception exists that this nation is wasteful in its use of materials and that such wasteful behavior must be regulated. The perception which dates at least to the Conservation Movement of the late Nineteenth Century is underscored by recent calls for the U.S. to establish a materials policy and to enact specific programs and policies to encourage conservation and recycling.(1) With the passage of the Resource Conservation and Recovery Act of 1976 (RCRA), it became official governmental policy to "promote the protection of health and the environment and to conserve valuable material and energy resources."(2) Conservation and recycling are to be encouraged through technical and financial assistance to state and local governments for new and improved methods of collection, separation, and recovery of solid waste as well as through new guidelines for collection, treatment, separation, recovery and disposal practices, and through programs of research and development.

The need for governmental intervention to stimulate resource conservation was argued in years past through reference to wasteful practices in natural resource development and material use. As informed observers are quick to point out, patterns of resource development and conservation are governed by market prices and that what appears to be wasteful behavior often is not. For example, if natural gas is flared in an oil field, it's because it is not profitable to capture and market the gas. If operators were forced to market the gas, society would sacrifice goods and services having a higher value than the gas which is captured. Indeed, Hotelling argued that private market forces generally provide for an optimal amount of resource conservation.

Although the same observations concerning alleged wasteful behavior are still made, a more sophisticated rationale for actions to promote conservation and recycling has been advanced in recent years. This rationale is based upon failures of the market system to provide in every instance the correct signals to those who develop resources and consume materials. A partial list of the potentially more significant sources of market failure includes institutional forces such affected materially by subsidies given to U.S. producers. Previous studies have made no attempt to estimate the impact of tax subsidies on the quantity of virgin minerals which are produced. The quantity effect is virtually certain to be larger than the price effect, again because of the importance of imports in domestic mineral consumption. With only slight changes in the U.S. producer price of a mineral, large shifts will occur in the percentage of the U.S. market which is supplied by domestic producers.

The impacts on recycling created by the subsidization of primary mineral production were the focus of a major research project for EPA.(7) In that study we found the probable quantity impacts on recycling to be quite small, at most 1 or 2 percent. Although the approach taken in our econometric modeling of competition between primary and secondary production tended to understate substitution possibilities, the price effects for primary minerals was probably overstated, implying that the estimated quanitity impacts may yet be reasonably accurate.

The tax treatment of standing timber confers a significant subsidy to the timber industry. Actually timber producers qualify for two subsidies: immediate expensing of most costs of growing timber, and capital gains treatment of the resultant gain in value upon harvest. Because of the liberal provision for expensive growing costs, most of the value of standing timber is treated as a capital gain. The maximum long-run price effect of these subsidies on the price of standing timber has been estimated to range from 35 to 45%.(8) The impacts are this large principally because the U.S. is an exporter of timber, and therefore domestic timber prices are determined by the costs of domestic production rather than those of world production.

Despite large price effects on timber, the impacts of the timber industry subsidies on the recycling of wastepaper are not likely to be large for a variety of reasons. First, the price of standing timber accounts for only about 12 percent of the cost of woodpulp, and it is woodpulp, not standing timber, which substitutes for recycled wastepaper. Second, the supply of wastepaper does not appear to be very responsive to changes in price, having an estimated price-elasticity of approximately .5.(9) Third, the substitution between woodpulp and wastepaper is far from perfect, at least in the short run as is evidenced historically by violent swings in the relative price of the two goods.

The subsidization of primary production, when considered in isolation of other market forces, clearly reduces overall economic efficiency. Investments in virgin material production are more lightly taxed than are their counterparts in recycling. As a consequence, the amount of investment in primary production is excessive and in recycling it is inadequate. As we have seen, the probable impacts on the quantity of material recycled are relatively minor. The question is whether the resulting gains in efficiency would repay efforts to eliminate tax subsidies to primary producers. This question has not been investigated in previous research, and consequently my remarks here will be brief.

It appears that on the grounds of administrative costs alone, a case could be made for removing the special tax subsidies for primary producers. Administering a complex system of subsidies, such as is now in place, imposes auditing costs for compliance and legal costs to adjudicate special situations. These situations inevitably arise as investors seek to maximize their tax subsidies.

Removal of the special subsidies for primary material producers would pose some difficult problems of equity. Many, if not most, of the mining and timber firms have acquired properties or have made major investments in company-owned properties after the tax subsidies were in place. In making new investments or adding to existing investments, these companies have computed an expected rate of return which includes the subsidy. In fact, the long-run, after-tax rates of return in mining and timber operations are much the same as in general manufacturing or in service industries. If the special subsidies in mining and forestry were eliminated, the existing operations would produce lower rates of return on existing investments. In other words, the market value of the investments would fall until the new post-tax rates of return were comparable to those offered by equally risky investments in other sectors of the economy.

as tax subsidies to virgin material production, vertical integration in primary production, labeling requirements for recycled goods, and the regulation of freight rates at inappropriate levels; externalities such as the failure to price correctly the disposal of post-consumer waste; and informational problems such as incorrect perceptions as to the quality of recycled materials.

In their general impact, all such sources of market failure lead to poor decisions from the perspective of overall social well-being. Individual actions which ordinarily would channel resources into their most highly-valued uses are misguided by the various forms of market failure. It is not sufficient, however, to argue that because there are market failures that correction through governmental intervention is desirable. One must recognize that intervention has its costs too. Moreover, there often exist significant legal and political obstacles which must be overcome before governmental action can be taken. Finally, it must be recognized that while there are sources of market failure which lead to inadequate conservation of resources and insufficient resource recovery, there exist countervailing forces such as state severance taxes, near-monopolistic control of natural resource development, and subsidization of resource recovery, all of which act to varying degrees to promote conservation and recycling. These should be considered in evaluating the necessity and desirability of intervention to correct particular forms of market failure.

The plan of this paper is to review prior research on impediments to conservation and recycling with a broad view as to the desirability of corrective action. Because prior research efforts have usually taken a narrow focus and not examined critical issues such as administrative and political obstacles to intervention, there remain many significant gaps in our understanding of precisely what actions, if any, are warranted. Major emphasis will be given to two of the aforementioned sources of market failure: the subsidization of virgin material production through the federal tax code, and the failure to price correctly the disposal of waste materials of both the post-consumer and hazardous or toxic variety.

TAX SUBSIDIES FOR VIRGIN MATERIAL PRODUCTION

The federal tax code permits significant income tax deductions for the production of primary materials, the most significant deduction historically being percent depletion.(3) Other tax subsidies include the expensing of exploration and development expenditures, the capital gains treatment of iron and coal royalties, the capital gains treatment of standing timber and the immediate expensing of many of the costs of planting and caring for a stand of timber. The total value of these subsidies exceeds several billion dollars per year. The major impact of these various tax code provisions is to reduce the cost of primary materials, thereby stimulating more rapid development and greater consumption than would otherwise occur. Recycled materials are placed at a competitive disadvantage with respect to price, serving to inhibit to a certain degree efforts to recover and reuse materials, particularly those extracted from the post-consumer waste stream.

The evolution of percent depletion as a tax deduction demonstrates that little thought was given to the probable impacts of these tax policies.(4) Rather, percent depletion developed through a continuing political tug-of-war in the Congress as a seemingly unending parade of special interest groups in mining sought and finally gained the prize of percentage depletion for their industry.

Estimating the quantitative impacts of tax subsidies such as percent depletion is difficult for a number of reasons. The most important of these are the largely unknown production functions in mining, the cost conditions for new mineral supplies, the pricing behavior of producers, and the demand functions for mineral outputs. In various studies the maximum potential price impacts of percent depletion on intermediate mineral outputs which compete with recycled materials have been estimated at from 1 or 2 percent up to about 10 percent, depending upon the mineral.(5-6) That these price effects are overstated is almost certain, particularly in view of the fact that the U.S. is a net importer of most minerals. Domestic prices are essentially determined by conditions on world markets and are not

On the grounds of equity towards the owners of existing investments, it appears that removal of the subsidies accorded to those investments would not be justified. A much preferred approach would be to phase a new system of taxation in gradually -- making it applicable only to new investments or new mineral discoveries. Even so, the equity issue would not disappear totally. Consider the treatment of an existing undeveloped mining claim. With percent depletion, the claim has a far higher value than if percent depletion were henceforth disallowed. Equity for the owner of the mining claim may dictate that depletion be allowed on this property. But then we would continue to encourage the excessive investment in mining on all existing mining claims -- and there are several million undeveloped claims on the public lands in the western states. In this situation, it appears that the attainment of greater efficiency is in a direct and irreconcilable conflict with common perceptions of equity. Furthermore, attempts to attain, even gradually, both efficiency and equity will almost certainly require a complicated and administratively costly system as the subsidies are phased out.

The political and legal obstacles in removing the special tax subsidies for timber and mining would likely be great. No industry would willingly acquiesce to a heavier tax burden or see existing investments marked down sharply in value. Any attempt to remove the subsidies would almost certainly encounter intense lobbying efforts from industry. Moreover, changing the tax code would require new tax legislation, and even without industry opposition this would be a difficult feat to accomplish.

Highlighting the analysis thus far, it appears that the special tax subsidies of mining and timber operations may have relatively large impacts on the use of domestic virgin material supplies relative to foreign supplies. The impacts on recycling, however, do not appear to be large. Any attempt to improve efficiency by removing the special tax subsidies would produce strong political opposition, particularly from Congressional representatives from the major mining and timber states. They and their constituents would not be pleased with the equity implications of doing away with the present system of preferential taxation.

An issue worthy of future research is whether it is possible to design an administratively feasible method for eliminating the special subsidies while simultaneously preserving intact the value of existing investments. If such an approach could be developed, political feasibility would be enhanced significantly.

PRICING THE COLLECTION AND DISPOSAL OF WASTE MATERIALS

The collection and disposal of post-consumer solid waste, commonly known as garbage or trash, is financed in various ways throughout the country.(10) Some cities and municipalities finance such activities wholly out of general property tax receipts. In other areas a flat monthly fee for collection and disposal is levied by the city or sometimes by the system operator if a private contractor is used. In a small minority of communities, the fee which is assessed varies with the quantity of waste generated by a household. Finally, in some communities, varying levels of service are available (e.g., curbside pickup or backyard pickup, and once or twice-weekly pickup), with the fee varying with the level of service.

From the standpoint of economic efficiency, these methods of financing and disposing of post-consumer waste leave much to be desired. Only rarely does the household pay a fee which corresponds to the marginal cost of providing the service. In many cases, the effective price for using additional service is zero. This is undesirable in that the efficient allocation of resources requires that price must equal marginal cost. The consequence of such incorrect pricing is that more waste collection and disposal services will be demanded than is socially optimal. Households will have inadequate incentives to consider alternative options such as composting of yard wastes (leaves and grass clippings), separating for recycling (paper, glass, and metal), or reducing their consumption of the goods and services which result in the generation of large volumes of residual solid wastes.

At least two solutions have been proposed to correct this problem. One is to institute marginal cost pricing on a local basis. The second is to impose a so-called "product charge" on the manufacture of all products destined for consumption. As will be seen shortly, neither solution is ideal.

Ideally, the disposal fee should be set at the marginal cost of collection and disposal. Therefore, an ideal set of disposal fees would vary with all of the factors which affect cost -- the quantity of material disposed of, the amount of service offered, the local wage rates for sanitary workers, and the cost of acquiring sites for waste disposal. Needless to say, the calculation of an ideal price schedule would be fairly complex.

Establishing the proper fee schedule is by no means the only difficulty that will be encountered if one wishes to establish theoretically efficient prices for disposal services. A very thorny issue arises in how the pricing system is to be administered.(11) Who will keep records and present bills to households? Several alternative mechanisms are possible -- records could be kept by sanitation workers; the use of marked plastic bags, sold only through authorized distributors, could be required; or a stamp could be required to be affixed to each container placed at curbside for pickup. All of these approaches have been tried in local experiments here and abroad. None of the approaches has gained widespread use -- in fact most of the experiments ended in apparent failure. Some systems were administratively cumbersome and costly while in others households objected to the inconveniences. In some cases, fears that illicit disposal and littering would increase, helped to curtail the experiments.

In assessing the desirability of instituting marginal cost pricing for solid waste services, one must have a clear understanding of the magnitude of the welfare loss which is created by present pricing systems. Only if the administrative costs of a marginal cost pricing system are less than the inefficiency costs imposed on society, would corrective action be warranted. Although a vigorous assessment of the existing welfare losses has not been made, the available evidence suggests that only modest losses are being incurred. The quantity of waste material which is generated by a household appears to be quite insensitive to the price of disposal services. This is to be expected if factors other than disposal cost such as tastes and preferences, income, and other prices, are the principal determinants of the quantity and composition of those goods which are purchased and ultimately diposed.

The product charge represents an attempt to create, on a national basis, a charge reflecting average disposal costs of about one cent per pound for all products which enter the household consumption and disposal stream.(12) The charge would be paid by manufacturers and would be based upon the virgin material content of the products. (Alternatively all materials used would be taxed but a rebate would be given for the use of secondary materials.) The product charge represents a sacrifice in efficiency for savings in administrative costs. Because the charge would be levied on a national basis there would be no reflection of local variation in collection and disposal costs. Furthermore, yard wastes, which constitute approximately one-half of all consumer solid waste, would go untaxed.

A major problem with the product charge concept is the fact that it will require new tax legislation which is notoriously difficult to pass in Congress.

The case for a change in the current system of solid waste disposal pricing cannot be made until it is shown that the gains in efficiency in some new system outweigh the additional administrative costs which would be incurred. Proponents of the product charge have not developed a convincing case that significant efficiency gains would accrue. Likewise, proponents of marginal cost pricing of solid waste disposal have not yet designed and validated an administratively inexpensive system of charges. Further research on the former and experimentation on the latter appear necessary and desirable before recommendations for change are made.

The disposal of toxic, hazardous, and polluting substances reflects another type of pricing failure in solid waste disposal. Where materials from either the industrial or post-consumer waste streams have the capacity to damage the environment or human health, it may be unwise for disposal to follow the typical pattern of burning or burial in a landfill. Although solid waste diposal prices could be adjusted to reflect the social costs of including these materials in the solid waste stream, a more efficient solution may be to encourage separation and different treatment for the especially toxic, hazardous or polluting wastes. Just as the Resource Conservation and Recovery Act of 1976 sets out special standards for generating, transporting, storing and disposing hazardous industrial wastes, so also might such special treatment be accorded these substances in the post-consumer waste stream.

A good example of this problem is provided by used lubricating oils, substances which are particularly likely to cause unwanted pollution of the water and air.(13) Unfortunately, consumers have long been encouraged by prices and other market forces to dispose of used oils in socially undesirable ways. Typically, a consumer's choices are limited to three main alternatives: including the oils in the solid waste stream, burying in one's backyard, or pouring down a storm sewer. Occasionally a waste oil recycler will accept such offerings. Service stations, which themselves generate and return for recycling large quantities of used lubricating oils, normally prefer not to accept the offerings of the "do it yourselfer." After all, the latter is effectively a competitor to the service station and although the station is paid for its used oil, the price may not justify the inconvenience of accepting a few quarts of oil from many individuals.

Potential solutions to this externality include (1) the use of a deposit system under which used oil must be returned to a vendor of lubricating oils for a refund of the deposit, (2) the prohibition of disposal in the municipal waste stream with the concomitant establishment of local used oil recycling centers, or requirements that vendors or service stations accept used oil, and (3) requiring that service stations accept oil which is offered by the do-it-yourselfer.

Because service stations already have facilities for receiving and storing used oil, the third alternative would impose few additional costs on society. Moreover, requiring service stations to accept used oil produces insignificant administrative burdens upon government agencies. It may impose slight burdens upon station operators, but this is balanced to an extent by the value of the oil which is received. The real difficulty with this alternative is that it requires new legislation. We might note in passing that the third alternative appears to be gaining acceptance. A number of states have passed used oil legislation patterned after a model statute drafted by staff of the Environmental Law Institute.(14)

The problems with a deposit system are that it too would require new legislation and in addition would impose administrative costs upon those selling lubricating oils. Their opposition to such an approach has effectively blocked further consideration of deposit systems.

Prohibitions on disposal in the municipal waste stream would be very difficult to enforce, effectively ruling out such an approach. Furthermore, if enforced, they could encourage illicit and environmentally more damaging methods of disposal such as surreptitious dumping in storm sewers.

OTHER SOURCES OF MARKET FAILURE

In the introduction we noted several other potential sources of market failure: vertical integration in primary production, labeling requirements, railroad freight rate regulation, and incorrect perceptions as to the quality of recycled materials. This section offers a brief review of these issues, possible solutions, and recommendations for further research on these topics.

Vertical integration in primary production which can encompass all stages of activity from the development of sources of raw material inputs to the manufacture of goods for final consumption, tends to inhibit reliance on secondary sources of supply. Users of raw material inputs prefer to rely upon the certain availability of firm-owned supplies rather than the sometimes chaotic markets for recycled materials. Only when company-owned supplies are inadequate to meet company needs is there a great pressure to acquire raw materials from other sources.

We might ask why vertical integration has occurred in so many of the industries which rely upon raw material inputs, and why the vertical integration has favored primary sources of raw material supply almost exclusively. Mancke noted that a driving force for vertical integration in the steel industry during the early Twentieth Century was a fear on the part of the steel firms, that an iron ore cartel could be established and that such a cartel could extract the economic rents then accruing to the steel industry.(15) Aside from the fact that industrial and post-consumer supplies of scrap constitute a lesser percentage of raw material inputs than does iron ore, the steel industry also must have realized that capturing control of the geographically widely dispersed supplies of scrap steel would be difficult to accomplish. Equally difficult would be the establishment of a scrap iron and steel cartel. Similar observations probably explain why paper companies have often integrated backward into the ownership of timber stands but have not attempted to gain control of sources of wastepaper supply.

For certain, vertical integration serves as a deterrent to the recovery of scrap materials, but it is not clear what, if any, policy action should be taken. Antitrust action could be initiated on the grounds of restraint of trade. Such an approach has the advantage that it lies within existing statutory authorities. Alternatively, with new legislation, incentive systems could be created to encourage firms to divest themselves of ownership of virgin material supplies and to acquire control of sources of secondary materials.

Labeling requirements for goods which contain recycled materials can act as a deterrent to resource recovery, particularly if the labels effectively create misunderstandings about product quality. Recent legislative action has sought to prohibit labeling requirements which discriminate against recycled oil. Section 383 of the recently enacted "Energy Policy and Conservation Act" reads in part: "No rule or order of the Federal Trade Commission may require any container of recycled oil to also bear a label containing any term, phrase, or description which connotes less than substantial equivalency of such recycled oil with new oil."(16) Whether parallel action covering other commodities is necessary or desirable should be studied further.

Railroad freight rate regulations allegedly discriminate against recycled commodities in favor of virgin materials. A number of studies have been conducted to probe this issue.(17-19) The most convincing of the studies show that on a weight basis virgin materials do travel for significantly lower prices than does the corresponding recycled material. But to show discrimination requires that one also assess the costs of service. If virgin materials happen to cost the railroads correspondingly less per ton to carry (perhaps because they are denser, or are less damaging to equipment, or are more easily loaded and unloaded), then there is no discrimination. Moreover, inasmuch as railroad freight rates are usually influenced by perceived elasticities of demand for transportation, commodities for which demand is thought to be inelastic will tend to have higher rates than commodities whose demand is more elastic. Scrap materials may have relatively inelastic demands for freight service and as a consequence may experience somewhat higher railroad transport costs than do virgin materials.

CONCLUSIONS

In a private free-enterprise economy decisions as to the amounts of materials to consume, the amounts to conserve, and the amounts to recycle are left to determination by market forces. In our mixed economy, governmental actions also influence these decisions. The basic thrust of the literature on resource use is that conservation and recycling should be fostered in order to assure a sufficient level of these worthwhile activities. The need to foster greater conservation and recycling has historically been based on a widespread belief that private market forces would not provide for a sufficient level of these activities. Economists have shown that this belief is generally invalid; more recently the calls made by the economics profession for policy action to encourage resource conservation and recycling have been based on arguments that private market decisionmakers receive incorrect signals and therefore make socially undesirable decisions.

These incorrect signals may arise from a variety of institutional and economic forces -- including institutional forces such as tax subsidies to virgin material production, vertical integration in primary production, labeling requirements for recycled goods, and the regulation of freight rates; externalities such as the failure to price correctly the disposal of post-consumer waste; and informational problems such as incorrect perceptions as to the quality of recycled materials. In general, all of these sources of market failure lead to poor decisions concerning resource use. Although the individual private decision-maker is maximizing his own welfare, this does not necessarily lead to socially optimal decisions when market failures are present.

From the perspective of public policy, the critical issue is whether intervention in resource markets is warranted and if so, what form the intervention should take. This paper has attempted to show that this question is complex and that many subsidiary questions must be resolved in a satisfactory manner before a particular policy prescription can be recommended. Some of these subsidiary issues concern such dimensions as the administrative costs of intervention, the equity implications of intervention, and the political and legal obstacles to intervention.

This paper reviewed in detail two sources of market failure -- the subsidization of virgin material production through the federal tax code and the incorrect pricing of consumer waste disposal -- and examined the desirability of a variety of alternative policy prescriptions for these problems. Both sources of market failure tend to inhibit conservation and recycling, but the analysis here shows that we are not yet prepared to advocate a particular solution in the form of further public intervention for either of these problems. The best policy may be inaction, but that can only be determined conclusively when more information is in hand.

REFERENCES

1. Anderson, R. C., "Evaluation of Economic Benefits of Resource Conservation," U.S. EPA, 600/5-78-015, 1978.
2. Resource Conservation and Recovery Act of 1976 (P.L. 94-580) § 1003.
3. Anderson, R. C. and R. D. Spiegelman, "The Impact of the Federal Tax Code on Resource Recovery," NTIS, PB 264 886, 1976.
4. Anderson, R. C., A. S. Miller, and R. D. Spiegelman, "U.S. Federal Tax Policy: The Evolution of Percentage Depletion for Minerals," Resources Policy, V. 3, No. 3, 1977, pp. 165-178.
5. Anderson and Spiegelman, op. cit.
6. Toder, E. J., "Federal Tax Policy and Recycling of Solid Waste Materials," U.S. Treasury Department, Preliminary Draft Report, Sept. 1978.
7. Anderson and Spiegelman, op. cit.
8. Toder, op. cit.
9. Anderson, R. C. and R. D. Spiegelman, "Tax Policy and Secondary Material Use," Journal of Environmental Economics and Management, V. 4, No. 1, 1977, pp. 68-82.
10. Lanen, W., "Efficiency of User Charges," presented at Workshop on Solid Waste Economics, Philadelphia, Pa., Sept. 19-20, 1978.
11. Stevens, B., "Administrative Costs of User Fees," presented at Workshop on Solid Waste Economics, Philadelphia, Pa., Sept. 19-20, 1978.
12. Buchanan, S., "Evaluating the Efficiency of the Solid Waste Charge," presented at Workshop on Solid Waste Economics, Philadelphia, Pa., Sept. 19-20, 1978.
13. Irwin, W. A. and R. A. Liroff, "Used Oil Law in the United States and Europe," U.S. EPA 600/5-74-025.
14. Irwin, W. A., "A Model Used Oil Recycling Act," report to Federal Energy Administration, July 1976.
15. Mancke, R., "The American Iron Ore and Steel Industries: Two Essays," unpublished Ph.D. dissertation, MIT, 1969.
16. 42 USC 6201 (P.L. 94-163).

17. Albrecht, O. W., "Shipping Wastes to Useful Places," Environmental Science and Technology, V. 10, No. 5, May 1976, pp. 440-442.

18. Resource Planning Institute, "Raw Materials Transportation Costs and Their Influence on the Use of Wastepaper and Scrap Iron and Steel," NTIS, PB 223-871, 1974.

19. Moshman Associates, "Transportation Rates and Costs for Selected Virgin and Secondary Commodities," NTIS, PB 233-871, 1974.

SMALL-SCALE AND LOW TECHNOLOGY RESOURCE RECOVERY

Gary L. Mitchell, PE
Charles W. Peterson
SCS Engineers
Reston, Virginia

ABSTRACT

A study was conducted to assess the applicability of various approaches to resource recovery to selected waste generators. The resource recovery systems and technologies were limited to those operating in the small-scale range, defined as less than 100 tons per day input, or those approaches considered to be low technology, defined as having more than 50 percent of operation and maintenance costs associated with labor, i.e., labor intensive. The generators included institutions, commercial sources, office building complexes, multi-unit residences and small cities.

An evaluation of seven potential systems led to the conclusion that two approaches were technically and economically feasible for application to the waste generators. The two systems identified were modular incineration with energy recovery and source separation. A detailed analysis of the application of these two systems to the waste stream generators led to determination of applicability of either or both approaches to resource recovery to each of the generators. It was found that modular incineration is generally applicable to only the largest examples of the waste generators studied. Similar conclusions were associated with source separation; however, this approach was found more applicable to smaller situations than was modular incineration. Recommendation for future research and development included more thorough waste characterization of the sources studied, investigation of the effects of building design on resource recovery feasibility, and a further study of systems not currently considered as proven technology.

INTRODUCTION

Approaches to the recovery of materials or energy from municipal wastes have been in operation for several years. This is particularly true of source separation and incineration with energy recovery. Most examples of these systems are associated with metropolitan areas with populations exceeding 100,000. Little information has, however,has been compiled on procedures for recovering resources from specific waste generators within metropolitan areas or in smaller cities.

Section 8002(d) of the Resource Recovery and Conservation Act of 1976 (RCRA) required the U.S. Environmental Protection Agency (EPA) to conduct a study of small-scale and low technology resource recovery. The purposes of the project were:

- To compile a comprehensive bibliography on small-scale and low technology resource recovery systems
- To determine solid waste characteristics and collection and disposal practices of selected small waste generators
- To analÿze small-scale and low technology resource recovery systems and evaluate applicability of the most feasible systems to the various waste generators
- To make recommendations for future research and development efforts.

DEFINITION AND SCOPE OF PROJECT

Small-scale systems were defined as technologies which operate at a maximum capacity of 100 tons per day with less than

50 percent of the operating and maintenance costs devoted to labor.* Thus, these small-scale systems are essentially smaller versions of high technology approaches to resource recovery. The small-scale systems' input would be mixed wastes from the sources identified with the output including separated materials and/or recovered energy.

Low technology systems were defined as having 50 percent or more of the operating and maintenance costs associated with labor. No limitations were placed on the input capacity of low technology systems. The principal low technology system in the United States is source separation; however, many approaches to material recovery could fit the definition if they were oriented to manual labor rather than mechanized operations.

The project focused on several types of small volume waste generators including the following:

- Institutions
  - Hospitals
  - Prisons
  - Universities
- Office Buildings
- Commercial Sources
  - Airports
  - Shopping Centers
- Multi-unit Residences
  - Garden or Low-rise Apartments
  - Mobile Home Parks
- Small Cities

The inclusion of some of these waste generators was required by the legislation directing this study. Others were included because it was felt that they were potential candidates for resource recovery operations. Some of the above sources had easily segregated portions of the waste streams containing materials amenable to recovery. Examples include the recovery of corrugated cardboard from prisons, universities, and shopping centers. Some of the waste generators were considered as likely on-site consumers of energy recovered from the incineration of their wastes. These included hospitals, prisons, universities, airports, shopping centers and low-rise apartments. Small cities were included essentially to complete the scope of potential resource recovery from municipalities.

APPROACH

Waste Characteristics and Generation Rates

In order to assess the applicability of resource recovery to these waste generators, information was needed on solid waste generation rates, waste composition, and typical collection and disposal practices. A search of the literature yielded very little information on the generators with the exception of small cities, office buildings, and hospitals. This lack of published data necessitated limited, informal, on-site waste characterization studies supplemented by telephone surveys.

The literature review and data collection efforts yielded the approximate waste composition and generation rates shown in Table 1. It should be noted that some of the waste generators were divided into subcategories, e.g., four different types of operations at airports and three different sizes of shopping centers; however, only one example of each source is shown in Table 1. Of particular interest were the units of measure associated with overall waste generation rates. Most of the literature reported some factor of waste generation per day or week, related to a measure of size or level of activity at the facility. The size measurement was often based on the number of persons using the facility, but also included floor areas (for shopping centers) and number of paid staff (hospitals). Composition data was taken from a limited number of sources in most cases, as was the overall waste generation rates. The effort to collect information on waste stream generators and applicable resource recovery technologies led to the development of a topical bibliography.

---

*Metric units of measure were not used in this project. It was felt that the user community was more accustomed to English units and that the degree of actual use of this report would decrease if metric units were reported. The use of English units in lieu of metric was approved by the Project Officer.

TABLE 1. APPROXIMATE WASTE COMPOSITION AND GENERATION RATES FOR SELECTED WASTE GENERATORS

	Percent of Total (Weight Basis)							
Type of Material	Airport Passenger Terminal	Regional Shopping Center	Hospitals	Prisons	Universities	Multi-Unit Residences	Office Buildings	Small Cities
Paper	71	28	40	37	55	35	87	29
Corrugated		52		22	10			
Glass	4	1	6	1	8	12	1	10
Metal	6	3	2	16	7	10	7	10
Plastics	5	8	15	8	3	5	1	3
Organics	5	2	25	10	10	27	4	38
Wood	3	2	12	6	7	11		4
Miscellaneous	6	4						6
TOTAL	100	100	100	100	100	100	100	100
Overall Waste Generation Rates	0.5 lb per passenger per day	200 lb per 1000 sq. ft. of gross leasable area per week	2 to 4.5 lb per paid staff member per day	4.5 lb per inmate per day	1 lb per student per day	2.7 lb per resident per day	1.5 lb per office worker per day	3.5 lb per person per day

The generation rates were found to be quite variable, depending upon the type of activity conducted. This was especially true of hospitals and prisons. Within hospitals such "heavy care" units as surgery and maternity had high generation figures, whereas, "light care" units such as psychiatric and administrative units generated much less waste. The generation rate for prisons is associated with residential and administrative aspects of these institutions and did not include any wastes generated by industrial or agricultural activities. The fairly extensive use of disposable items is reflected in the generation rate and the quantities of paper and plastics.

The generation rates at universities depends upon the types of wastes included. The generation rate shown does not include wastes from agricultural or medical schools or landscaping, demolition, and construction wastes. Likewise, it was noted that sources of recyclable materials at universities, particularly paper, were easy to identify, with approximately 80 percent of all paper coming from office and classroom areas. A high percentage of this paper is recyclable.

Office buildings are notable for the very high percentage of paper. Much of this is high-grade paper and computer cards and printout which often command premium prices. Numerous office buildings of governmental agencies and private firms practice source separation of high-grade paper. A relatively small amount of organics is generated by office buildings without food service facilities. The percentage of organics increases significantly for office buildings with food service facilities.

Relatively large quantities of organics are shown coming from multi-unit residences and small cities. This is due to the fact that both garbage and landscaping wastes are included.

The data in Table 1 are derived from a relatively small sampling of information from the specific sources, with the exception of hospitals, office buildings, and small cities. Thus, in assessing the feasibility of resource recovery in a specific situation, a waste characterization study should be completed to determine the composition and quantity of wastes being generated at that location.

Technology System Evaluation

System Criteria--

The next step in this study was to collect information and evaluate the current state-of-the-art approaches to resource recovery for the their applicability to the waste generators selected. Information concerning the state-of-the-art, applicability, and costs associated with material processing components was obtained from a variety of sources including published material and through direct contact with equipment users and manufacturers. No site visits to resource recovery operations were made during this project. Gathering of information was not limited to the United States. As part of the project, the First World Recycling Congress was attended. The five-day Congress was held in Basel, Switzerland and included technical papers and equipment displays from some 20 countries worldwide.

Unit process components considered technologically proven at the 100 ton per day level or less were assembled into resource recovery systems applicable to the waste generators. Operational and technical aspects of each system were analyzed and a cost analysis developed which was used to estimate net disposal costs per ton of input.

For purposes of the study components of resource recovery systems were considered technologically proven, if, at 100 tons per day or less, the component has:

- Operated at full-scale for at least one year
- Produced the desired product in a marketable form.

This definition eliminated components in the pilot-scale or in shake-down tests. Likewise, it eliminated those components generating a product that is not marketable; i.e., no market exists for the material or has existed in the very recent past. The above definition was applied to various resource recovery system components. The components of small-scale systems initially considered included the following:

acid hydrolysis conversion units
air classifiers
aluminum magnets
composting equipment
froth flotation units
magnetic separators
methane digesters
modular incinerators
pyrolytic units
shredders
trommel screens

Application of the criteria for a component to be technologically proven prior to further consideration led to the elimination of several components. These are listed below along with the reason for elimination:

- Acid hydrolysis conversion unit -- considered to be in experimental or pilot stage.
- Aluminum magnets -- unable to assess effectiveness of the one operational unit due to small amounts of aluminum in waste stream. Other installations considered to be in shake-down status.
- Froth flotation -- considered to be in shake-down status. Although high purity product (99%) has been achieved, it still does not meet container industry specifications.
- Methane digesters -- pilot-scale plant for solid wastes and sewage sludge in operation. No system in operation at commercial scale.
- Pyrolysis -- two small operating units considered to be in demonstration or shake-down status.

The remaining components were "assembled" into six, small-scale systems for further analysis:

- Ferrous Recovery
- Compost Preparation
- Compost Preparation with Ferrous Recovery
- RDF Preparation with Ferrous Recovery
- Incineration with Heat Recovery
- Incineration with Heat and Ferrous Recovery

Application of System and Cost Analyses--

Next, scenarios were developed describing the features of each of the above systems, their limitations, and their applicability. This led to the development of a cost analysis of each. In order to evaluate the systems as uniformly as possible, common assumptions were applied, as follows:

- All systems to be operated at 100 tons per day input.
- Hauling and disposal costs for non-recovered waste from the processing facility were estimated at $7 per ton.
- Uniform costs for labor were applied.
- An average mid-1977 market value for recovered material was used.
- The value of energy recovered was equated to the cost of the least expensive fossil fuel from which the same amount of energy could be recovered.

An example cost analysis is shown in Table 2. Specific assumptions associated with modular incineration are shown in the table.

In the area of low technology systems only source separation was considered, and a scenario was developed describing a typical source separation program applicable to a small city. The great variability of source separation and its applicability to several of the waste generators precluded the development of scenarios and the resulting cost analyses of more than one source separation program.

Overall Evaluation--

As a result of an overall evaluation considering costs and other factors, modular incineration with heat recovery (without ferrous recovery) and source separation emerged as the highest rated systems. Additionally, these were the systems with the lowest cost per ton. An area of potential concern for modular incinerators is air pollution control. While several

TABLE 2. EXAMPLE COST ANALYSIS
MODULAR INCINERATOR WITH ENERGY RECOVERY[1] (100 TPD)

		Initial Costs	Life (Years)	Amortization Factor (8%)	Annual Costs
CAPITAL COSTS ($1,000)					
Incinerator and boiler, complete in place[2]		$1800	15	0.117	$210
Auxiliary Equipment		50	5	0.250	13
Small Front-End Loader	40				
Office Furniture, Refuse Bins	10				
Construction & Land		396	20	0.101	40
Building: $9500\ \text{ft}^2$ @ $\$30/\text{ft}^2$	288				
Site Development: 20% of bldg.	58				
Land: 5 acres @ $10,000/acre	50				
TOTAL		$2246			$263
OPERATING COSTS ($1,000)					
Labor:[2] 4 operators @ $48 1 supervisor @ $16					64
Supplies: 3% of labor & maint.					3
Energy:[4] Supplemental fuel		$36.0			
Mobile loader		3.2			
Lighting		0.7			
Heat building		1.3			41
Maintenance: 3% of total capital costs					66
Miscellaneous: (taxes, licenses, insurance, administrative and management costs) 1% of total initial capital costs					22
TOTAL					$196
TOTAL ANNUAL SYSTEM COSTS ($1,000)					$459
COSTS/REVENUES PER TON ($/ton)					
System Cost					$ 17.65
System Revenue					8.08
Net System					9.57
Landfill					2.11
Total Net					$ 11.68

TABLE 2. (Continued)

Footnotes:

[1] Data calculated by SCS Enginners from literature and vendor sources.

[2] Includes 5 25-TPD units. Incinerators are designed to operate on a 24-hour basis. The extra unit provides reserve capacity for maintenance.

[3] Operators are on duty for 8-hour shifts. The shifts are split to allow for continuous operation, 5 days per week. Wage rate is $5.80 per hour, which includes fringe benefits of 15 percent. The supervisor is on duty for one 8-hour shift at $7.80 per hour.

[4] Energy: Supplemental fuel is consumed at a rate of 5 percent of the BTU value of the input refuse. Operating conditions:

• Thermal value of refuse	5,000 BTU/pound
• Supplemental fuel	Natural Gas
• Cost of gas	$0.2776/therm
• Thermal value of therm	100,000 BTU

Mobile Equipment - operation conditions are:

• Gasoline Consumption	2.5 gallons/hour
- Cost	$0.60/gallon

[5] Revenue Factors:

• Percent combustibles in wastestream	80%
• Recovery rate	90%
• Market value: substitute value of coal	$1154/100 tons of combustible refuse @ 5000 BTU/pound

[6] Cost Factors:

• Weight Reduction	70%
• Cost to haul to landfill and disposal	$7/ton

installations have met State standards, it is possible that some units will require external air pollution control devices. The approach used in evaluating the systems is described below.

Those systems with apparent technical and economic feasibility and desirability for application to the waste stream generators were subjectively evaluated. In order to evaluate the systems, rating criteria were selected that represent the characteristics (other than economics) of greatest concern to small waste generators. Site-specific factors, such as public acceptance, were not rated, although they are extremely important. The criteria selected were essentially qualitative in nature and thus were rated accordingly. Three major categories of criteria were performance, environmental acceptability, and marketability of recovered product. These were further subdivided into more detailed criteria; an explanation of the approach used to rate each is shown in Table 3.

Consideration of information available in the literature and through contacts with system owners and operators lead to the evaluation of the systems using the above criteria. The results are shown in Table 4. A review of the ratings in Table 4 led to the elimination of several systems from further evaluation as to their applicability to the waste stream generators. Reasons for eliminating these systems are summarized below:

- RDF -- high costs, market uncertainty, and possibile problems associated with storage and transport of the material
- Ferrous Recovery -- high costs and price fluctuations for recovered ferrous
- Compost -- high costs, large capital investment and virtually no market for the product.

Application of Technologies to Waste Stream Generators

Summary--

The applicability of modular incineration or source separation or a combination of the two to any of the waste stream generators was then evaluated on the basis of the overall system costs. The inclusion of resource recovery was considered appropriate and feasible in all situations where the overall waste management costs with the inclusion of resource recovery were equal to or less than the waste management costs prior to any change. Costs for collection and disposal of wastes from all sources except small cities was estimated to be $28 per ton, which includes rental of bulk waste containers. For small cities the disposal costs of $7 per ton was used. It was assumed that the city would have to collect the wastes whether they used landfill disposal or hauled it to a resource recovery facility; thus, only the cost of disposing of unrecovered material impacted on this analysis. The results of this analysis indicated situations for waste stream generators in which one or the other or both approaches to resource recovery was less expensive than current disposal and thus considered feasible. Overall feasibility is shown in Table 5.

As can be seen from the table, there are only a few situations in which either modular incineration or source separation or a combination of both were unequivocally considered feasible for a particular waste generator. In most instances, resource recovery was considered viable only for the largest examples of each waste generator, thus exemplifying some economies of scale associated with these operations. For those waste generators where the combination of both approaches to resource recovery was indicated as feasible, it should be understood that the decision was based upon meeting the more stringent of the requirements for either incineration or source separation. For example, both modular incineration and source separation would be considered feasible in office buildings if there is at least 4,000 employees.

Only multi-unit residences (low-rise apartments and mobile home parks) were not considered amenable to resource recovery. Neither normally has enough residents to generate the required quantity of materials or mixed wastes. Likewise, there are virtually no examples of situations where recovered energy could be used in the mobile home park or in an apartment building, except possibly a large apartment complete with a central boiler/hot water system.

Particular note should be made of the indicated feasibility of modular

TABLE 3. SYSTEM RATING CRITERIA

I. PERFORMANCE

A. Reliability: System and components proven to perform dependably and with minimum down-time.

Rating	Description
High	Proven performance with high reliability
Medium	Adequate performance with adequate reliability
Unacceptable	Inadequate performance with inconsistent reliability

B. Degree of Waste Volume Reduction

Rating	Description
High	>60%
Medium	30-59%
Low	0-29%

C. Freedom from Maintenance/Simplicity

Rating	Description
High	Simple; minimal skills required for operation; few or no moving parts
Medium	Moderate; intermediate in mechanical complexity; operation requires some degree of skill and/or training
Low	Complex; involves sophisticated mechanical equipment; skilled and trained operators required

II. ENVIRONMENTAL ACCEPTABILITY

A. Meets all minimum standards for air, noise, water and land pollution

Rating	Description
Acceptable	Complies with minimum standards
Unacceptable	Does not meet standards

B. Maximizes resource recovery within technological limits

Rating	Description
High	Recovers maximum number of resources; >60% of waste
Medium	Recovers moderate number of resources; 30-59% of waste
Low	Recovers few resources; <29% of waste stream

III. MARKETABILITY OF RECOVERED PRODUCT(S)

Rating	Description
High	Product(s) have ready markets
Medium	Product(s) are somewhat marketable, but prices subject to cyclical swings
Low	Product(s) difficult to market or have very low value

TABLE 4. SYSTEM RATING

	System Rating Criteria (100 TPD System)						
	Reliability	Waste Volume Reduction	Freedom from Maintenance; i.e., Simplicity	Environmental Standards	Resource Recovery	Marketability of Product(s)	Net Cost/Ton*
Ferrous Recovery	Medium	Medium	Low	Acceptable	Low	Low	$15.38
Compost	Medium	Medium	Low	Acceptable	Medium	Low	26.70
Compost with Ferrous Recovery	Medium	High	Low	Acceptable	High	Low	26.05
RDF with Ferrous Recovery	Medium	High	Low	Acceptable	High	Medium	13.61
Incineration with Energy Recovery	High	High	Medium	Acceptable**	High	High	11.68
Incineration with Ferrous and Energy Recovery	Medium	High	Low	Acceptable**	High	Medium	11.95
Source Separation	Medium	Medium	High	Acceptable	Medium	Medium	8.16

* Cost of operating system minus revenues plus disposal of non-recovered material.

** May require external air pollution control equipment.

TABLE 5. FEASIBILITY OF RESOURCE RECOVERY SYSTEMS TO WASTE GENERATORS

Waste Generator	Modular Incineration w/ Energy Recovery	Source Separation	Both
Small Cities	If disposal costs are more than $12 per ton	Newspaper--above 13,000 population @ 30% participation Fe, Al, glass and newspaper--above 22,000 population @ 30% participation	No
Office Buildings	If more than 4,000 employees	High-grade paper down to 75 employees	Yes
Airports	At major airports	Corrugated, sometimes	Yes
Shopping Centers	Yes	Corrugated	Yes
Low-rise Apartments	No	No	No
Mobile Home Parks	No	No	No
Prisons	Only the largest; 1,500+ inmates	Corrugated	Yes
Hospitals	If more than 500 beds	No	No
Universities	If more than 5,000 students	High-grade paper	Yes

incineration to small cities. The disposal costs of $7 per ton was used for small cities because it was used earlier in the cost analyses of the seven systems originally considered technologically proven. This cost may be too low, particularly for small disposal operations; e.g., 100 TPD, that are truly sanitary landfills. Likewise, the value of the energy recovered at any particular location may be greater than the $1 per million BTU assumed in Table 2. Several small cities are cost effectively using this method of resource recovery.

It cannot be overemphasized that the feasibility of any approach to resource recovery is highly site-dependent. The evaluations made in the report were based upon assumed costs for solid waste management and values of recovered energy and materials. There are, and will be, exceptions to the findings of this report. Thus, it is imperative that any waste generator evaluating resource recovery make an individual feasibility study conducted by competent, experienced personnel prior to making any commitments.

Specific Applications--

Situations in which resource recovery was considered feasible were presented as shown in Tables 6 through 13. These tables were developed to present a guide to managers in a preliminary determination of resource recovery feasibility. In the example for universities in Table 6, the application of modular incineration is shown in the upper portion of the table. A consistent waste composition was assumed for each of the first six conditions. This resulted in an estimated energy content of the waste measured in BTU per pound. Next, various waste generation rates were assumed ranging from 1 to 2 pounds per student per day.

At this point, the equipment available for modular incineration with energy recovery was considered. Currently, equipment is available to operate on a continuous basis (24 hours per day) or on a batch basis (8 hours per day). Both were considered applicable to universities as it was assumed that recovered energy would be in the form of steam connected to an existing steam generating plant on the campus. The different periods of operation are

TABLE 6. RESOURCE RECOVERY APPLICABLE TO UNIVERSITIES

MODULAR INCINERATION	On-Site Energy Use	Materials Market	BTU/ lb Waste	TPD	Generation Rate	Waste Composition	Recovery Rate	Existing System Cost/Day	New System Net Cost/ Day
Condition 1 22,000 students	Yes- $\$1/10^6$ BTU	N/A	6,000	10	1 lb/ student/ day	Paper 65% Misc 4% Plastic 3% Other 18% Organics 10%	24 hr/ day	$308	$275
Condition 2 14,670 students	•	•	•	•	1.5 lb/ student/ day	• •	•	•	•
Condition 3 11,000 students	•	•	•	•	2 lb/ student/ day	• •	•	•	•
Condition 4 8,800 students	•	•	•	4.4	1 lb/ student/ day	• •	8 hr/ day	$123	$108
Condition 5 5,870 students	•	•	•	•	1.5 lb/ student/ day	• •	•	•	•
Condition 6 4,400 students	•	•	•	•	2 lb/ student/ day	• •	•	•	•
SOURCE SEPARATION									
Condition 1 9,750 students	N/A	High-grade paper- $55/ton		4.9	1 lb/ student/ day	High-grade paper 15%	50%	$137	$137
Condition 2 6,500 students	•	•		•	1.5 lbs/ student/ day				
Condition 3 4,875 students	•	•		•	2 lb/ student/ day				
MODULAR INCINERATION and SOURCE SEPARATION	On-Site Energy Use	Materials Market	BTU/ lb Waste	TPD	Generation Rate	Waste Composition	Recovery Rate	Existing System Cost/Day	New System Net Cost/ Day
Condition 1 23,800 students	$\$1/10^6$ BTU	High-grade paper- $55/ton	5,370	11.9 (11 TPD MOD INC)	1 lb/ student/ day	High-grade paper 15%	24 hr/ day 50%	$333	$300
Condition 2 15,870 students	•	•	•	•	1.5 lb/ student/ day	•	•	•	•
Condition 3 11,900 students	•	•	•	•	2 lb/ student/ day	•	•	•	•
Condition 4 9,600 students	•	•	•	4.8 (4.4 TPD MOD INC)		•	8 hr/ day 50%	$134	$127
Condition 5 6,400 students	•	•	•	•		•	•	•	•
Condition 6 4,800 students	•	•	•	•		•	•	•	•

noted in the column entitled Recovery Rate. A value for the recovered energy was then assumed in order to evaluate the net cost of the solid waste management system including resource recovery.

The following step was to calculate the minimum number of students that would generate the required quantity of waste needed to fuel the incinerator (the six conditions for modular incineration). Thus, if an administrator of a university knew or assumed that the waste composition was similar to that shown and that the value of the recovered energy was also similarly assumed ($1 per million BTU) and knew what the waste generation rate was and that it ranged between 1 and 2 pounds per student per day, he could determine the feasibility of modular incineration with energy recovery.

As an example, if the waste generation rate at a university was known to be 1.5 pounds per student per day with the composition and energy costs similar to that shown on Table 6, it would be possible to incinerate the wastes and recover energy either on a 24-hour-per- day basis or 8-hour-per-day basis (conditions 2 and 5 respectively). With approximately 6,000 students or more, Condition 5 is met and a batch-type incinerator operating 8 hours a day appears appropriate and economically feasible. Note that the system with energy recovery is estimated to cost $108 per day as compared to the existing system cost of $123 per day. If the university had approximately 15,000 or more students, a 24-hour-per-day incineration and recovery system appears to be appropriate and feasible.

Source separation was evaluated in a similar manner in the center portion of Table 6. High-grade paper was the only material that was assumed recoverable with a price assumed as shown under Materials Market. Likewise, the concentration of high-grade paper was assumed as shown. By knowing the overall waste generation rate (again, between 1 and 2 pounds per student per day) and projecting a 50 percent recovery rate, a college administrator could determine if he should make a more detailed study of table. This is essentially a combination of the two upper evaluations with one major exception. There was a correction for the energy content of the waste due to the removal of high-grade paper through source separation. Note the reduction of energy content from 6,000 to 5,370 BTU per pound. The applicability of resource recovery to the other waste generators is shown in Tables 7 through 13.

RESEARCH AND DEVELOPMENT NEEDS

The final objective of the project was to make recommendations for further expenditures of efforts and funds in the area of research and development associated with small-scale and low technology resource recovery. Three areas were recommended for further study:

- In-depth waste characterization studies of small waste generators included in this study, especially shopping centers, prisons, universities, and airports.
- Studies to determine how changes in building design could facilitate and encourage resource recovery. Shopping centers appear to be the most fruitful area for these efforts.
- Analysis of resource recovery systems in the developmental stage with a likelihood of successful application to small generators. The systems recommended for further analysis included production of RDF and the application of vermicomposting to solid waste management. When the production of RDF at large resource recovery facilities increases and the use of this fuel increases, markets for RDF will develop and become stable. This may give rise to situations where small generators (probably small cities) near markets can economically produce RDF. Vermicomposting is essentially the only low technology resource recovery system that is applicable to such waste stream generators as prisons, universities, and small cities.

TABLE 7. RESOURCE RECOVERY APPLICABLE TO SHOPPING CENTERS

MODULAR INCINERATION	On-Site Energy Use	Materials Market	BTU/ lb Waste	TPD	Generation Rate	Waste Composition	Recovery Rate	Existing System Cost/Day	New System Net Cost/ Day
Condition 1 800,000 SFGLA*	Yes- $\$1/10^6$ BTU	N/A	7000	8	20 lbs/1000 SFGLA/day	Paper 80% Plastic 7.5% Other 12.5%	24 hr/ day	$224	$220
Condition 2 640,000 SFGLA	•	•	•	•	25 lbs/1000 SFGLA/day	•	•	•	•
Condition 3 535,000 SFGLA	•	•	•	•	30 lbs/1000 SFGLA/day	•	•	•	•
Condition 4 400,000 SFGLA	•	•	•	4	20 lbs/1000 SFGLA/day	•	8 hr/ day	$112	$104
Condition 5 320,000 SFGLA	•	•	•	•	25 lbs/1000 SFGLA/day	•	•	•	•
Condition 6 265,000 SFGLA	•	•	•	•	30 lbs/1000 SFGLA/day	•	•	•	•
SOURCE SEPARATION									
Condition 1 280,000 SFGLA	N/A	Corrugated $10/ton		2.8	20 lbs/1000 SFGLA/day	Corrugated 52%	70%	$ 78	$ 78
Condition 2 224,000 SFGLA		•		•	25 lbs/1000 SFGLA/day		•	•	•
Condition 3 190,000 SFGLA		•		•	30 lbs/1000 SFGLA/day	•	•	•	•
MODULAR INCINERATION and SOURCE SEPARATION	On-Site Energy Use	Materials Market	BTU/ lb Waste	TPD	Generation Rate	Waste Composition	Recovery Rate	Existing System Cost/Day	New System Net Cost/ Day
Condition 1 1,560,000 SFGLA	$\$1/10^6$ BTU	Corrugated $10/ton	4116	15.6 (10 TPD MOD INC)	20 lbs/1000 SFGLA/day	Corrugated 52%	24 hr/ day 70%	$437	$404
Condition 2 1,250,000 SFGLA	•	•	•	•	25 lbs/1000 SFGLA/day	•	•	•	•
Condition 3 1,040,000 SFGLA	•	•	•	•	30 lbs/1000 SFGLA/day	•	•	•	•
Condition 4 630,000 SFGLA	•	•	•	6.3 (4 TPD MOD INC)	20 lbs/1000 SFGLA/day	•	8 hr/ day 70%	$176	$163
Condition 5 504,000 SFGLA	•	•	•	•	25 lbs/1000 SFGLA/day	•	•	•	•
Condition 6 420,000 SFGLA	•	•	•	•	30 lbs/1000 SFGLA/day	•	•	•	•

* SFGLA: Square Feet Gross Leasable Area.

TABLE 8. RESOURCE RECOVERY APPLICABLE TO OFFICE BUILDINGS

MODULAR INCINERATION	On-Site Energy Use	Materials Market	BTU/ lb Waste	TPD	Generation Rate	Waste Composition	Recovery Rate	Existing System Cost/Day	New System Net Cost/ Day
Condition 16,000 employees	Yes- $1/10^6$ BTU	N/A	7000	8	1 lb/ employee/ day	Paper 87 % Plastic 1.5% Other 14.5%	24 hr/ day	$224	$220
Condition 2 10,670 employees	•	•	•	•	1.5 lb/ employee/ day	•	•	•	•
Condition 3 8,000 employees	•	•	•	•	2 lbs/ employee/ day	•	•	•	•
Condition 4 8,000 employees	•	•	•	4	1 lb/ employee/ day	•	8 hr/ day	$112	$104
Condition 5 5,350 employees	•	•	•	•	1.5 lb/ employee/ day	•	•	•	•
Condition 6 4,000 employees	•	•	•	•	2 lb/ employee/ day	•	•	•	•
SOURCE SEPARATION									
Condition 1 150 employees	N/A	High-grade paper- $55/ton		.075	1 lb/ employee/ day	High-grade paper 43%	70%	$2.10	$2.10
Condition 2 100 employees	•	•		•	1.5 lb/ employee/ day	•	•	•	•
Condition 3 75 employees	•	•		•	2 lbs/ employee/ day	•	•	•	•
MODULAR INCINERATION and SOURCE SEPARATION	**One-Site Energy Use**	**Materials Market**	**BTU/ lb Waste**	**TPD**	**Generation Rate**	**Waste Composition**	**Recovery Rate**	**Existing System Cost/Day**	**New System Net Cost/ Day**
Condition 1 20,000 employees	Yes- $1/10^6$ BTU	High-grade paper $55/ton	4480	10 (7 TPD MOD INC)	1 lb/ employee/ day	High-grade paper 43%	24 hr/ day 70%	$280	$248
Condition 2 13,335 employees	•	•	•	•	1.5 lb/ employee/ day	•	•	•	•
Condition 3 10,000 employees	•	•	•	•	2 lb/ employee/ day	•	•	•	•
Condition 4 9,400 employees	•	•	•	4.7 (3.3 TPD MOD INC)	1 lb/ employee/ day	•	8 hr/ day 70%	$132	$118
Condition 5 6,270 employees	•	•	•	•	1.5 lb/ employee/ day	•	•	•	•
Condition 6 4,700 employees	•	•	•	•	2 lb/ employee/ day	•	•	•	•

TABLE 9. RESOURCE RECOVERY APPLICABLE TO AIRPORTS

MODULAR INCINERATION	On-Site Energy Use	Materials Market	BTU/ lb Waste	TPD	Generation Rate	Waste Composition	Recovery Rate	Existing System Cost/Day	New System Net Cost/ Day
Condition 1 80,000 passengers/day	Yes- $\$1/10^{6}$ BTU		6500	10	.25 lb/ passenger/ day	Paper 50% Organics 15% Plastic 10% Other 16% Wood 8%	24 hr/ day	$280	$269
Condition 2 40,000 passengers/day	▪		▪	▪	.5 lb/ passenger/ day	▪ ▪	▪	▪	▪
Condition 3 13,350 passengers/day	▪		▪	▪	1.5 lb/ passenger/ day	▪ ▪	▪	▪	▪
Condition 4 32,000 passengers/day	▪		▪	4	.25 lb/ passenger/ day	▪ ▪	8 hr/ day	$112	$107
Condition 5 10,000 passengers/day	▪		▪	▪	.5 lb/ passenger/ day	▪ ▪	▪	▪	▪
Condition 6 5,350 passenger/day	▪		▪	▪	1.5 lb/ passenger/ day	▪ ▪	▪	▪	▪
SOURCE SEPARATION									
Condition 1 Airfreight area, 200 TPD Cargo		Corrugated $30/ton		.7	7 lbs/ton cargo/ day	Corrugated 32%	70%	$ 9	$ 9
Condition 2 Aircraft Maintenance Base-1,150 employees		▪		1.3	2.2 lbs/ employee/ day	Corrugated 36%	70%	$ 18	$ 18

TABLE 10. RESOURCE RECOVERY APPLICABLE TO SMALL CITIES

SOURCE SEPARATION	On-Site Energy Use	Materials Market	BTU/ lb Waste	TPD	Generation Rate	Waste Composition	Recovery Rate	Existing System Cost/Day	New System Net Cost/ Day
Condition 1 13,600 people	N/A	Newspaper- $40/ton baled	N/A	14	2.5 lb/ capital/ day	Newspaper 9%	50%	$ 29	$ 29
Condition 2 28,000 people	▪	▪	▪	34	▪	▪	30%	$ 43	$ 43
Condition 1 4,800 people	▪	Newspaper- $20/ton loose	▪	6	▪	▪	50%	$ 5	$ 5
Condition 2 12,800 people	▪	▪	▪	16	▪	▪	30%	$ 11	$ 11
Condition 1 12,800 people	▪	Fe-$40/ton AL-$340/ton Glass- $30/ton	▪	16	2.5 lbs/ capital/ day	Ferrous 9% AL 10% Glass 13%	50%	$102	$102
Condition 2 25,600 people	▪	▪	▪	31	▪	▪	30%	$115	$115
Condition 1 11,200 people	▪ ▪	Fe-$40/ton AL-$340/ton Glass- $30/ton Newspaper- $40/ton/ baled	▪	14	▪	▪	50%	$116	$116
Condition 2 21,600 people	▪	▪	▪	27	▪	▪	30%	$136	$136

TABLE 11. RESOURCE RECOVERY APPLICABLE TO PRISONS

MODULAR INCINERATION	On-Site Energy Use	Materials Market	BTU/ lb Waste	TPD	Generation Rate	Waste Composition	Recovery Rate	Existing System Cost/Day	New System Net Cost/ Day
Condition 1 5,500 inmates	Yes- $1/10⁶ BTU	N/A	5500	11	4 lbs/ inmate/ day	Paper 59% Other 23% Plastic 8% Organics 10%	24 hr/ day	$308	$284
Condition 2 4,400 inmates	•	•	•	•	5 lbs/ inmate/ day	• •	•	•	•
Condition 3 3,670 inmates	•	•	•	•	6 lbs/ inmate/ day	• •	•	•	•
Condition 4 4,400 inmates	•	•	•	4.4	4 lbs/ inmate/ day	• •	8 hr/ day	$123	$112
Condition 5 1,760 inmates	•	•	•	•	5 lbs/ inmate/ day	• •	•	•	•
Condition 6 1,470 inmates	•	•	•	•	6 lbs/ inmate/ day	• •	•	•	•
SOURCE SEPARATION									
Condition 1 750 inmates	N/A	Corrugated $30/ton	•	1.5	4 lbs/ inmate/ day	Corrugated 23%	80%	$ 42	$ 42
Condition 2 600 inmates	•	•	•	•	5 lbs/ inmate/ day	•	•	•	•
Condition 3 500 inmates	•	•	•	•	6 lbs/ inmate/ day	•	•	•	•

MODULAR INCINERATION and SOURCE SEPARATION	On-Site Energy Use	Materials Market	BTU/ lb Waste	TPD	Generation Rate	Waste Composition	Recovery Rate	Existing System Cost/Day	New System Net Cost/ Day
Condition 1 2,700 inmates	Yes- $1/10⁶ BTU	Corrugated $30/ton	3,960	5.4	4 lbs/ inmate/ day	Corrugated 23%	8 hr/ day 80%	$151	$120
Condition 2 2,160 inmates	•	•	•	•	5 lbs inmate/ day	•	•	•	•
Condition 3 1,800 inmates	•	•	•	•	6 lbs/ inmate/ day	•	•	•	•

TABLE 12. RESOURCE RECOVERY APPLICABLE TO GARDEN APARTMENTS

MODULAR INCINERATION	On-Site Energy Use	Materials Market	BTU/ lb Waste	TPD	Generation Rate	Waste Composition	Recovery Rate	Existing System Cost/Day	New System Net Cost/ Day
Condition 1 11,000 tenants	Yes- $1/10⁶ BTU	N/A	5000	11	2 lbs/ tenant/ day	Paper 35% Misc 11% Plastic 4.5% Other 22.5% Organics 27%	24 hr/ day	$308	$293
Condition 2 8,800 tenants	•	•	•	•	2.5 lbs/ tenant/ day	• •	•	•	•
Condition 3 7,335 tenants	•	•	•	•	3 lbs/ tenant/ day	• •	•	•	•
Condition 4 4,400 tenants	•	•	•	4.4	2 lbs/ tenant/ day	• •	8 hr/ day	$123	$115
Condition 5 3,520 tenants	•	•	•	•	2.5 lb/ tenant/ day	• •	•	•	•
Condition 6 2,935 tenants	•	•	•	•	3 lb/ tenant/ day	• •	•	•	•

TABLE 13. RESOURCE RECOVERY APPLICABLE TO HOSPITALS

MODULAR INCINERATION	On-Site Energy Use	Materials Market	BTU/ lb Waste	TPD	Generation Rate	Waste Composition		Recovery Rate	Existing System Cost/Day	New System Net Cost/ Day
Condition 1 1,600 beds	Yes- $1/10^6$ BTU	N/A	7000	8	10 lbs/ bed/day	Paper 40% Plastic 15% Organics 25%	Misc 10% Other 10%	24 hr/ day	$224	$220
Condition 2 1,067 beds	"	"	"	"	15 lbs/ bed/day	"	"	"	"	"
Condition 3 800 beds	"	"	"	"	20 lbs/ bed/day	"	"	"	"	"
Condition 4 640 beds	"	"	"	"	25 lbs/ bed/day	"	"	"	"	"
Condition 5 800 beds	"	"	"	4	10 lbs/ bed/day	"	"	8 hr/ day	$112	$104
Condition 6 533 beds	"	"	"	"	15 lbs/ bed/day	"	"	"	"	"
Condition 7 400 beds	"	"	"	"	20 lbs/ bed/day	"	"	"	"	"
Condition 8 320 beds	"	"	"	"	25 lbs/ bed/day	"	"	"	"	"

COMPATIBILITY OF SOURCE SEPARATION AND MIXED-WASTE PROCESSING FOR RESOURCE RECOVERY

HARRY H. FIEDLER
BELUR N. MURTHY

GILBERT ASSOCIATES, INC.
READING, PENNSYLVANIA

ABSTRACT

Source separation is a procedure by which materials may be recovered from a waste stream and subsequently put to higher use. More specifically, this procedure is commonly imposed upon municipal solid waste before treatment in a mixed-waste processing facility.

This study examines the issues surrounding the compatibility of five source separation scenarios upon four of the most frequently encountered mixed-waste processes and suggests a methodology by which the characteristics and requirements unique to a specific community may be used to arrive at the most compatible combination of source separation and mixed-waste processing for that particular community.

The compatibility evaluation is accomplished by quantifying, to the extent possible, data pertaining to combinations of source separation and mixed-waste processing in four major areas of concern - conservation, environmental, economic, and institutional. The last area is primarily subjective due to its considerable dependence upon non-quantifiable social and legal considerations.

The major areas of concern are then prioritized depending upon the characteristics and requirements of the community. Following this, the most compatible combination from each area of concern for the specific community is identified. Finally, the prioritization considerations are applied to the identified most compatible combinations to arrive at the source separation scenario which overall is most compatible for the community.

INTRODUCTION

Every year, people in the United States discard 140 million tons of residential waste. In so doing, a number of environmental problems, ranging from air and water pollution to the removal of land from productive use are created. Of the 3.7 pounds of waste an average American discards each day, about 85% could be used to produce energy. Overall, about 25% could be recovered as material suitable for reuse or recycling.

Recognizing the energy potential of this waste stream, the Environmental Protection Agency (EPA) and other organizations have attempted to initiate actions - reducing quantity of waste directed to landfill, recycling usable materials, and combusting the organic constituents - to recover energy values.

Two principal technologies are available to achieve this goal, namely, source separation and mixed-waste processing. The EPA has taken the position that both technologies will be needed for effective resource recovery, a position which immediately raises the question as to whether the two technologies are compatible. Compounding this uncertainty, every community which is interested in ascertaining the most compatible combination of technologies, has its own site specific characteristics and requirements; accordingly, the technology combination which is most compatible for one community is not necessarily the most compatible for another.

In the following sections, source separation and mixed-waste processing technologies will be briefly reviewed. Following this is a brief discussion of the most important issues, results of quantitative analysis, and conclusions. Thereafter, a method is suggested by which communities can determine the most compatible combination of technologies. "Baselyn", a hypothetical community, is used as an example to test the methodology. Finally, overall conclusions are presented.

RESOURCE RECOVERY ALTERNATIVES

The alternatives available for resource recovery can be classified into source separation and mixed-waste processing.

Source Separation

In source separation, the primary responsibility for sorting and recovering materials lies with the waste generator: home owners, businesses, schools, etc. Currently, the most appropriate waste materials recoverable through source separation are aluminum, ferrous metals, paper, and glass.

The common alternatives available for source separation are:

- recycling centers
- separation of office paper
- separation of corrugated paper
- separate collection of newsprint and other paper
- separate collection of various materials
- beverage container deposits

In this study, a typical case of each of these source separation alternatives, except the recycling centers, has been considered for developing and evaluating the resource recovery compatibility assessment method. The recycling centers were excluded because the total impact of such a system on the waste flow of the community is relatively small, and the cost and resources invested in such a system are far greater than for the other methods.

Significant features of the five source separation scenarios considered are shown in Exhibit 1. Curb-side collection, handling and disposal of separated wastes are considered to be similar to the method practiced at Somerville and Marblehead(1). The recovered materials are sold to an intermediate processor for sorting, packaging, and resale to manufacturers.

Mixed Waste Processing

Modern mixed-waste processing facilities are complex and capital intensive. To reduce amortization costs per unit of municipal solid waste, a long-term commitment is necessary. Sophisticated planning, management and marketing are required. Most such facilities recover ferrous metal and energy in the form of refuse derived fuel (RDF) or steam. Some facilities also recover glass, primarily with trommels. RDF is usually recovered in modern facilities by air classification.

In this study, the following mixed-waste processes have been selected as typical commercial alternatives:

- o unprocessed waterwall combustion and ferrous recovery (UWCF)
- o processed waterwall combustion and ferrous recovery (PWCF)
- o refuse derived fuel production and ferrous recovery (RDFF)
- o modular incineration (MI)

Significant features of these alternatives are presented in Exhibit 2. More detailed descriptions of the mixed-waste processes are available in the literature(1-4).

"Baselyn", a Hypothetical Community

In order to assess the relative compatibilities of various source separation scenarios with commercially available mixed waste processing alternatives, a nationally typical hypothetical community, Baselyn, has been considered(4).

Baselyn has 108,000 inhabitants, with an average population density of 1,930 per square mile, and is located near a major metropolitan area.

There are approximately 24,000 single family homes in Baselyn. Real cities whose population and density statistics are similar to those of Baselyn include Pasadena, California; Lakewood, Colorado; Waterbury, Connecticut; Hollywood, Florida; New Bedford, Massachusetts; Ann Arbor, Michigan; Woodbridge, New Jersey; Albany, New York; and Canton, Ohio. Approximately 60% of the families own their own home. The median income is $12,000 per year and the median education level is 12.4 years.

The city's sanitation department collects solid waste from all households in Baselyn. Prior to the source separation program, the department employed 60 people and 10 packer trucks (capacity: 20 yd^3 each) for waste collection. Each truck was operated by a crew of three. In addition, the department employed 60 people for administration, maintenance, and other duties. Collection and disposal costs are approximately $5 per household, per month.

Waste is collected at curbside once a week. Each resident generates 3.7 lb of waste per day (the national average), so the department collected 200 tons per day before the source separation program began. Exhibit 3 presents the composition of solid waste in Baselyn.

The collection trucks unload at a transfer station located within the city limits. This station, operated by two people, has a compactor that loads the waste into 80 yd^3 trailers. From the transfer station, waste is hauled to a sanitary landfill that the county maintains in a rural area, 25 miles away. Baselyn uses approximately 7 acres per year, and over 150 acres are available for landfill.

Commercial establishments must contract with private companies for the collection of their waste. This waste is delivered directly to the county landfill. The county charges the city and private companies a tipping fee of $12 per ton.

Ten miles from Baselyn, there is a materials processor willing to buy paper, glass, and cans. Current prices are (FOB):

Newspaper	$30/ton
Corrugated paper	$30/ton
High grade paper	$60/ton
Mixed glass and cans	$10/ton

The mixed-waste processing facility is assumed to have a capcity of 1,000 tons/day, enough to process the combined wastes from Baselyn and four additional communities of similar characteristics and size.

The effect of the various source separation scenarios on the quantities of materials recovered, before the solid wastes are sent for mixed-waste processing, is shown in Exhibit 4.

The Baselyn area meets the existing national ambient air quality standards.

Fixed and Expanded Service Areas

Since source separation results in decreased waste quantities entering the mixed-waste processing facility, it may be economically desirable to make up the shortage of waste flow with mixed solid wastes collected from an area outside the five communities, each of which is considered similar to Baselyn. The effect of including such an expanded service area on the overall economics of waste disposal is compared with those of a fixed service area in this study.

The concepts of fixed and expanded service areas are graphically represented in Exhibit 5.

COMPATIBILITY: AREAS OF CONCERN

The entire concept of compatibility hinges upon whose viewpoint is being examined. As such, the issues of greatest importance differ according to the viewpoint of the observer, be it the plant operator, municipality, or the nation as a whole. For example, the plant operator is most interested in knowing whether source separation scenarios will decrease his profitability or increase the amount of pollutants released to the atmosphere. The municipality, on the other hand, is most concerned about the cost for disposal of the community's solid waste as well as the future availability of proper landfill capacity. Still other issues are of prime importance to the nation as a whole, namely, the depletion of natural resources and net energy consumption. This list of sample issues is not complete; however, it does identify some of the most important ones. Furthermore, some of the issues are composites of a number of sub-issues. For example, plant operation profitability is dependent upon the institutional issues of assured supply of solid waste, contractual determination of tipping fee, and assured revenues from saleable products. The following quantitative analysis of the combinations of technology in the conservation, environmental and economic areas of concern are necessary to determine the impact of each of the technology combinations upon an individual issue. Since the institutional issues can not be quantified, they will be treated subjectively.

Conservation

The effect of each source separation scenario on the net energy recoverable from the resource recovery system in the fixed or expanded service area has been calculated from the equation:

$$\eta_E = (E_S + \Sigma E_M - E_C)/E_{MSW}$$

where η_E = net energy recovery efficiency of the resource recovery system.

E_s = energy recovered ultimately as steam from the mixed waste processing facility.

E_m = sum of the net energies conserved by recycling instead of manufacturing from original raw materials - the materials recovered from source separation and mixed waste processing.

E_c = energy consumed by the resource recovery system, i.e., mixed-waste processing facility operation, collection and transportation of source separated and mixed wastes.

E_{msw} = energy content of the municipal solid wastes being collected in the service area.

The effect of source separation on the energy recoverable is shown in Exhibit 6 as steam from the mixed-waste processing unit.

The overall energy balance is represented by Exhibit 7. In this exhibit, the quantity of material or energy in the various exit streams will vary depending on the particular combination of source separation and mixed-waste processing being studied, and will be zero in some cases. Since the average composition of the mixed waste and that of the stream entering the mixed-waste processing facility are the same in both fixed and expanded areas, η_E for any SS and MWP combination remains unchanged for the two areas. The results, shown in Exhibit 8, indicate, in general, that beverage container recovery and high multi-material source separation contribute most to energy conservation.

Environmental Effects

Two factors are considered within the environmental area of concern: residual loadings to landfill and air emissions.

Residual to landfill is a direct measure of the reduction in tons of residual directed to final disposal as a result of each source separation and mixed-waste processing combination.

Air emissions are determined by using coefficients for each option that reflect the quantity of pollutants emitted to the atmosphere for each ton of waste processed. Calculations are made for the following pollutants: sulfur oxides (SO_x), nitrogen oxides (NO_x), particulates, and hydrocarbons.

1) Residual to landfill

The total quantity of waste remaining after each source separation program is the amount to be directed to landfill or to the mixed-waste processing facility. Residual to landfill (Exhibit 9) may vary by a factor of 1.8, from 135 to 239 tons. Since the residuals are so much smaller - both in volume and mass - than the inputs, any of the mixed-waste processing systems yields a substantial reduction in landfill requirement.

2) Air emissions

The following assumptions were used in analyzing the emissions:

- o Particulates produced in pre- or post-processing of the waste or residual is insignificant compared to that produced in processing and will be captured in a baghouse or recycled to the process in the air input steam.
- o The excess air assumed in burning and the standard cubic feet of flue gas produced per pound of waste processed were taken to be as follows:

Technology Option	Percent Excess Air	scf/lb
Unprocessed waterwall	75	75
Processed waterwall	50	65
RDF	50	65
Modular incineration	50	65

- o The air residuals were ratioed on the basis of heat inputs, which were taken as follows:

Source Separation	Btu's/Day
Multimaterial, high	7.65×10^9
Multimaterial, low	8.08×10^9
Newsprint, high	8.48×10^9
Newsprint, low	8.96×10^9
Beverage containers	9.19×10^9

The results of Exhibit 10 indicate that source separation scenarios will result in negligible production of particulates, SO_2, NO_x and hydrocarbons.

For large sources, an applicable EPA standard for particulates may be 0.1 lb/10^6 Btu's, which is equivalent to 0.46 tons/day in the present case. Hence, all mixed-waste processing options may require particular emission controls, with the two incinerator types requiring the most control.

Emissions of SO_2 are not generally a problem, due to the low sulfur content of the waste. Minimal cleanup, such as wet particulate removal, should suffice for control. Alternatively, one may conclude that the figures are sufficiently close to the limit so that the errors make the necessity of control problematical. Probably, no control will be needed for SO_2 to meet legal standards.

The EPA limit on NO_x, which is 0.7 lb/10^6 Btu and which may not apply to these processes, calculates to 3.22 tons/day.

There does not appear to be any relevant national hydrocarbon standard.

In general, only particulate emissions were high enough to present potentially significant problems for all combined alternatives involving mixed-waste processing facilities. High newsprint separation at the source produces a significant reduction in particulate emissions for all options. For other pollutants, emissions are generally low and source separation produces only a small change in the ratings.

Economic

The economic effects of imposing source separation on a mixed-waste processing facility were assessed by calculating the total costs of processing municipal solid waste in fixed and expanded service areas. The total cost was determined by subtracting revenues from capital and operating costs. Municipal ownership of the processing facility via General Obligation Bonds was assumed. The following equation was used to compute the total cost:

$$C_T = ((C_{SS} + C_{MWP} + (C_L + C_{AO} + C_M + C_U) + C_{TL} + C_{DL})) + (I_{CT} + I_D + C_S) - (R_P + R_F + R_G + R_A + R_S + R_R)$$

where,

C_{SS} = Collection and transportation costs of source separated materials

C_{MWP} = Collection and transportation costs of charge stock to the mixed-waste processing facility

C_L = Labor cost

C_{AO} = Administrative and overhead costs

C_M = Cost of materials including expendable supplies and equipment replacement

C_U = Utility costs

C_{TL} = Transportation cost of material to landfill

C_{DL} = Dump cost at the landfill (tipping fee)

I_{CT} = Interest on capital invested during construction

I_D = Debt service charges

C_S = Amortized start-up cost

R_P = Revenue derived from newsprint sales

R_F = Reveue derived from ferrous material sales

R_G = Revenue derived from glass sales

R_A = Revenue derived from aluminum sales

R_S = Revenue derived from steam sales

R_R = Revenue derived from refuse-derived fuel (RDF) sales

All costs were converted to mid-1977 dollars by using escalation or de-escalation factors and the Chemical Engineering (CE) plant index. An annual inflation rate of 6% was assumed. The annual charge for principal and interest is based on a 20 year life of all the facilities with a 1 year actual construction/start-up period; therefore, the bond issue is for a period of 21 years. We assume a sinking fund is established with 21 equal payments at an interest rate of 7 percent, and the bond principal is repaid at the end of the 21 year period. Costs of $25.85/ton, $5.00/ton and $12.00/ton were used for C_{MWP}, C_{TL}, and C_{DL}, respectively. Ferrous metal sales were set at $39/ton.

The results of the calculations, shown in Exhibits 11 and 12, indicate that high multi-material separation results in the lowest processing cost.

Institutional

1) Contracts:

Well-written contracts are the means by which potential adverse effects of source separation can be mitigated for a plant operator. The underlying need for the contracts is not only maintenance of profitability for the operator, but also assurance to the capital investors that their investment will be appropriately repaid.

Maintenance of profitability is predicated upon an assured supply of solid waste, tipping fee and acceptance of recycled products at a specific price. Contractual noncompliance of any of these elements can seriously jeopardize, if not defeat, economic viability of the operation. Furthermore, the investors must have a reasonable assurance that profitability will be at least adequate to cover principal and interest payments over the life of the project, or else they will not invest the capital. Since investment degree of risk is directly related to interest rate, a proposed facility without ironclad contractual safeguards against potential adverse economic effects resulting from source separation may still be financed. One method involves paying a higher interest rate to compensate for the higher risk, although this method is not without limitations. Another method involves issuance of Municipal Bonds - Revenue or General Obligation. With the former, the facility revenue is the source of the principal and interest payments with the interest rate dependent upon the degree of risk. For the latter, the full faith and taxing power of the municipality stands behind the principal and interest payments. As may be expected, General Obligation Bonds command a lower interest rate than Revenue Bonds.

2) Facility Maintenance

Facility maintenance is directly related to the quantity of glass contained within the solid waste stream charged to the processing facility.(5) Although this factor is a technical one, which directly affects operating costs, it is included within the institutional area due to the unavailability of reproducible quantitative data.

3) Employment

A low unemployment rate is desirable for all communities. Implementation of source separation will require additional personnel, estimated at 10-20% depending upon the scenario elected and degree of administrative control. In descending order, source separation personnel requirements are multimaterial, beverage containers and newsprint only. Implementation of source separation is not expected to significantly affect a plant operator's labor force.

4) Community Well-Being

The issue of whether a combination of technologies is compatible with the concept of community well-being is somewhat nebulous. Community well-being, when expressed as the reduction in community expense for solid waste disposal and a contribution to national recycling efforts, is indeed enhanced by implementation of resource recovery methods. The descending order of compatibility for the community, and the plant operator's position are the same as for the preceding "Employment" sub-section.

METHODOLOGY FOR ASSESSING COMPATIBILITY

The objective of this section is to develop a methodology that an interested party can use to determine which combination of source separation and mixed-waste processing is most compatible for their particular needs. An example is given to illustrate the use of the methodology.

Methodology

1) Order of Priority

Determine the relative importance existing between the conservation, environmental, economic and institutional areas of concern.

2) Combination Selection

Select from each of the four areas of concern the most compatible combination of source separation and mixed-waste processing as measured by the quantitative evaluator for the area, viz.,

Conservation - % efficiencies
Environmental - tons/day
Economic - $/ton
Institutional - Subjective

3) Compatibility Determination

Apply the priorities established in (1) above to the combinations selected in (2) above. This will result in weighted combinations from which the overall most compatible combination will be selected.

Sample Calculation

"Baselyn", the hypothetical community previously described, is the basis for the sample calculation. To simplify the analysis, it is assumed that Baselyn already has an unprocessed waterwall combustion facility, complete with ferrous recovery, and that only a fixed service area is available. Any other mixed-waste processing facility could have been selected for this example because no particular type of facility is favored in this study.

1) Order of Priority

Determination of the order of importance of the four areas of concern is shown in this section. The community decision makers have decided that conservation is of little concern to them and should have little bearing in the final analysis.

Adequate landfill space - good for approximately 21 years with the current population - is available, national ambient air quality standards are easily met, and no prohibitory landfill bills are anticipated. Taking these factors into consideration, it was concluded that environmental considerations are slightly greater than the level of importance given conservation.

The community or a private operator may own and operate the mixed-waste processing facility. In either case, firm contractual commitments are very important. The people have a sense of community responsibility and feel that the project's success is important. Although the unemployment rate is close to the national average, the community would be pleased if it were less. Based upon these facts, institutional considerations are felt to be important and should receive more recognition in the final analysis than either conservation or environmental considerations.

The national economic pinch is hurting this middle class community; accordingly, the greatest importance has been assigned to the lowest cost overall method of solid waste disposal.

2) Combination Selections

The conservation selection is accomplished by referring to Exhibits 6 and 8 and selecting the best of the source separation scenarios from the column representing the unprocessed waterwall combustion process. Doing this, the beverage container scenario turns out to be the best for both the percent Btu recovery as steam and percent net energy efficiency with 65% and 73%, respectively.

Following the same procedure with Exhibit 9, the high multi-material scenario has the best rating with the lowest residual to landfill figure of 135 tons/day. From Exhibit 10, four values - particulates, sulfur dioxide, oxides of nitrogen and hydrocarbons - are shown, representing tons/day of pollutants discharged to the atmosphere. The data shows that the high multi-material scenario has the best rating for all four residuals. Therefore, for the environmental area of concern, high multi-material is the best choice.

The economic choice is obtained by referring to Exhibit 11 and selecting the lowest dollars/ton cost. High multi-material recovery is the choice at $26.30.

The institutional selection is more difficult due to its subjective nature. If the contracts are well-written and result in as much protection as possible with appropriate relief upon the event of non-compliance, there is no real distinction between the impacts of the source separation scenarios. However, considering the factor of degree of wear in the mixed-waste processing facility due to glass, it is known with subjective certainty that the least quantity is desired.(2) Therefore, for the contracts portion of the institutional area of concern, if ironclad contracts are broken and commensurate relief is subsequently granted, the fact that the beverage container scenario prompted the abrogation would result in the greatest benefit to the facility operator. The interests of reduced unemployment and community well-being are best served by the high multi-materials scenario due to the greater number of people employed and in the quantity of useful material recovered. Since the employment and well-being issues are somewhat overlapping, their average result is given approximately the same weight as for the contractual obligation. The institutional area best choice is therefore split evenly between the beverage and high multi-material scenarios.

3) Compatibility Determination

This is the point where "it's all put together". Referring to the following summary table, high multi-material recovery is the most compatible source separation scenario to combine with the unprocessed waterwall combustion process in Baselyn.

SUMMARY TABLE

Compatibility Determination Matrix

Area of Concern	Priority	Most Compatible Source Separation Scenario
Conservation	Least important	Beverage container
Environmental	3rd most important	Multi-material, high
Economic	Most important	Multi-material, high
Institutional	2nd most important	Equally divided between high multi-material and beverage container

Although this selection was relatively clear-cut in Baselyn due to the preponderance of the high multi-material scenario in the highest priority rankings, it could be more difficult in other cases. In such an event, numerical ratings applied as priorities may be useful. Using Baselyn as a simplified example, if a total importance of 100% is attributed to the priority associated with the four areas of concern, then 40% thereof could be considered a reasonable quantitative weight of the "most important" priority applied to the economic area. Following this line of reasoning, 30% may be attributed to the industrial area, 17% to environmental, and 13% to conservation. Applying these weights to each of the individual source separation scenarios in the third column of the summary table and adding the results for the like scenarios, high multi-recovery would be the most compatible with 72% out of 100% - the same result obtained subjectively.

CONCLUSIONS

Selection of the optimum resource recovery system for a community is currently, at best, a most difficult determination. The methodology suggested in this paper provides a way in which one of the most important components - compatibility of source separation and mixed waste processing - of the optimum selection process may be accomplished. Application of this methodology to a hypothetical community "Baselyn" has resulted in the conclusion that high multi-material recovery is the most compatible source separation scenario to combine with an unprocessed waterwall combustion facility with ferrous recovery in a fixed service area of a community with the characteristics, requirements and priorities of Baselyn.

The authors recognize that the current state of the art of U.S. resource recovery systems is relatively unsophisticated; however, they hope that their efforts will be of assistance to the decision-makers attempting to optimize the implementation of resource recovery systems most responsive to the needs of American communities.

ACKNOWLEDGEMENT

This study has been sponsored by the U.S. Environmental Protection Agency under Contract No. 68-03-2645

References

1. U.S. EPA, Office of Solid Wastes, "Fourth Report to Congress: Resource Recovery and Waste Reduction", EPA Report No. SW-600, August 1, 1977.

2. Wilson, E. M., et al., "Engineering and Economic Analysis of Waste to Energy Systems", The Ralph M. Parsons Co., Report to U.S. EPA under Contract No. 68-02-2101, June 1977.

3. Jones, J., "Converting Solid Wastes and Residues to Fuel", Chemical Engineering, 85(1), p 87-94, 1978

4. Fiedler, H., et al, "Compatibility of Source Separation and Mixed-Waste Processing for Resource Recovery", Gilbert Associates and Resource Planning Associates, Report being prepared for EPA under Contract No. 68-03-2645, 1979.

5. "Resource Recovery", Solid Wastes Management, 1979 Sanitation Industry Yearbook, 16th Edition, p 46, December 30, 1978.

EXHIBIT 1

SOURCE SEPARATION SCENARIOS

Case	Features
1. Multi-material Recovery, High	Multi-material source separation and high-grade office paper and corrugated paper separation. Waste is separated into: 1) mixed paper; 2) clear glass and cans mixed; 3) colored glass and cans mixed; and 4) remaining wastes. Commercial office and corrugated papers are separately collected and sold to manufacturers. Recovery efficiency ranges from 12 to 60 percent of each type of material in the waste stream.
2. Multi-material Recovery, Low	Multi-material separation of homeowner waste with a lower recovery of paper, glass and metals. No recovery of office or corrugated paper in effect. Waste is separated into: 1) mixed papers; 2) mixed bottles and cans; and 3) remaining wastes. The overall recovery efficiency ranges from 12 to 42 percent.
3. Newsprint, Recovery, High	Separate collection of newsprint only. Approximately 60 percent of newsprint in the solid waste stream is recovered.
4. Newsprint, Recovery, Low	Separate collection of newsprint only; approximately 20 percent of newsprint is recovered.
5. Beverage Container Recovery	A beverage container deposit system imposed through legislation. Residents return containers directly to retail stores, or refund facilities. Approximately 90 percent of beverage containers are recovered. The existing community arrangements for collection and disposal of the remaining mixed municipal wastes are not affected.

EXHIBIT 2

MIXED-WASTE PROCESSING ALTERNATIVES

Alternative	Features
1. Unprocessed Waterwall Combustion and Ferrous Recovery	Mass burning of collected mixed waste, usually in a thick bed (up to 34') on a moving grate. Magnetic separation of ferrous material after incineration. Metallic tubes in the walls of the incinerator carry water which is converted to steam. Capacities range from 50 to 1,200 tons/day of mixed solid waste. Residue after incineration is usually sent to a landfill. Process requires additional pollution control equipment. Examples: Chicago, Illinois; Harrisburg, Pennsylvania; Nashville, Tennessee; Saugus, Massachusetts.
2. Processed Waterwall Combustion and Ferrous Recovery	Mechanical processing of the mixed waste to concentrate the combustible fraction and to reduce particle size. Ferrous material is magnetically separated from the non-combustible portion of the waste before incineration. Shredded and classified waste is introduced into the furnace by mechanical or pneumatic feeder. Burning waste is semisuspended and falls on a traveling grate to complete combustion in a thin bed. Steam recovery is through the water walls. Capacity range: 50 to 1,200 tons/day. Additional pollution control equipment is required. Examples: Norfolk, Virginia; Akron, Ohio; Oceanside, New York.
3. Refuse Derived Fuel (RDF) Production and Ferrous Recovery	Shredding, tromelling, air classification and magnetic separation results in separation of a combustible portion that is either pelletized, briquetted, extruded, or directly used as fuel in either a dedicated or auxiliary boiler. RDF may be formed wet or dry. Examples: RDF dedicated - Ames, Iowa; Akron, Ohio; RDF - auxiliary - St. Louis, Missouri; Milwaukee, Wisconsin; Bridgeport, Connecticut; Washington, D. C. (NCRR); Wet RDF (Black-Clawson) - Franklin, Ohio; and Hempstead, New York. Capacity range: 100 to 2,000 tons/day. Minimum pollution control equipment required.
4. Modular Incineration	Module capacities: less than 50 tons/day of mixed waste. Minimum pollution control equipment is required. Batch and continuous flow units are available. Preprocessing of mixed waste is not required. Coils in the incinerator generate steam. Economically suitable for smaller communities (800 to 200,000 population). Modules provide flexibility for expansion. Example. Siloam Spring, Arkansas.

EXHIBIT 3

COMPOSITION OF SOLID WASTE IN BASELYN

Component	Percentage			Quantity Collected Daily - tons		
PAPER	38.9			77.8		
Newsprint		7.5			15.0	
Office		3.5			7.0	
Corrugated		11.0			22.0	
Others		16.9			33.8	
GLASS	9.8			19.6		
Beer and soft drink		5.0			10.0	
Other		4.8			9.6	
METAL	4.9			9.8		
Ferrous		4.1			8.2	
Beer & soft drink			1.0			2.0
Other			3.1			6.2
Non-ferrous		0.8			1.6	
Beer & soft drink			0.5			1.0
Other			0.3			0.6
REMAINING WASTE*	46.4			92.8		
	100.0			200.0		

---

* Includes organic materials, wood, plastics, clothing, and other non-durable goods.

EXHIBIT 4

SOURCE SEPARATION MATERIALS RECOVERY

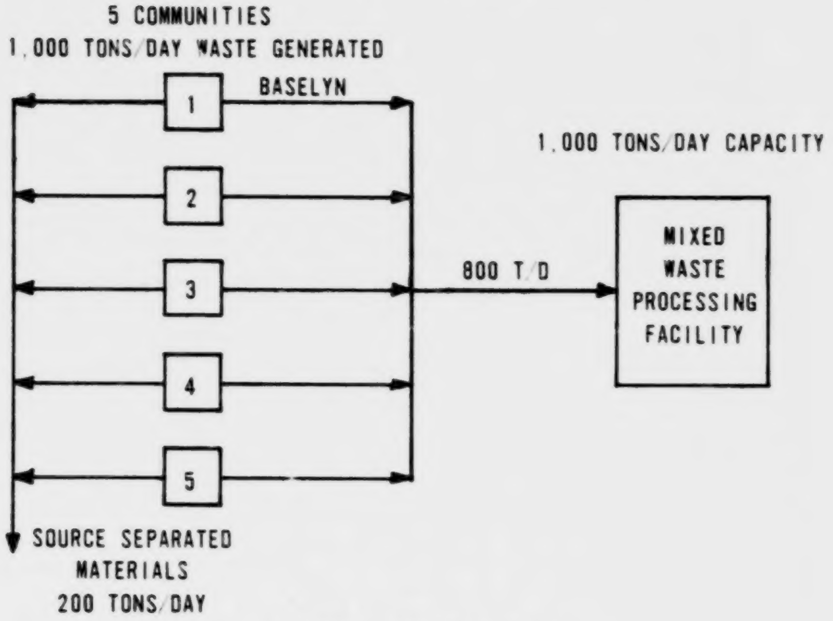
	Source Separated Material* in Tons per day and Percent of Total Waste Generated											
	Newsprint and Other Paper		Corrugated		Office		Glass and Metals		Total Recovered Waste		Remaining Mixed Waste	
Case	Tons	%	Tons	%	Tons	%	Tons	%	Tons	%	Tons	%
1. Multi-material recovery, high	13.4	6.7	5.5	2.8	1.8	9.0	14.4	7.2	35.1	17.6	164.9	82.4
2. Multi-material recovery, low	8.3	4.2					5.4	2.7	13.7	6.9	186.3	93.1
3. Newsprint recovery, high	9.0	4.5							9.0	4.5	191.0	95.5
4. Newsprint recovery, low	3.0	1.5							3.0	1.5	197.0	98.5
5. Beverage							11.7	9.0	11.7	9.0	188.3	91.0

---

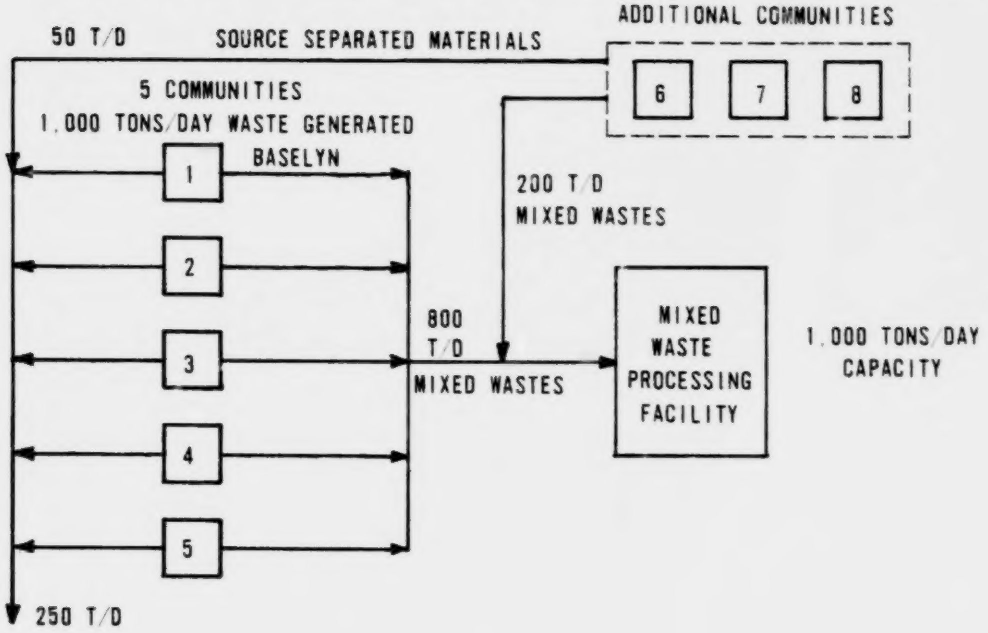
* Total waste generation in Baselyn is 200 tons per day.

EXHIBIT 5

FIXED AND EXPANDED SERVICE AREAS


5 COMMUNITIES
1,000 TONS/DAY WASTE GENERATED
BASELYN
1
2
3
4
5
1,000 TONS/DAY CAPACITY
800 T/D
MIXED WASTE PROCESSING FACILITY
SOURCE SEPARATED MATERIALS
200 TONS/DAY

FIXED SERVICE AREA


ADDITIONAL COMMUNITIES
50 T/D
SOURCE SEPARATED MATERIALS
6
7
8
5 COMMUNITIES
1,000 TONS/DAY WASTE GENERATED
BASELYN
1
2
3
4
5
200 T/D
MIXED WASTES
800
T/D
MIXED WASTES
MIXED WASTE PROCESSING FACILITY
1,000 TONS/DAY CAPACITY
250 T/D

EXPANDED SERVICE AREA

EXHIBIT 6

CONSERVATION - ENERGY RECOVERY AS STEAM, %
(Fixed or Expanded Service Area)

	Mixed Waste Processing Alternative			
Source Separation Scenario:	UWCF	PWCF	RDFF	MI
Multi-Material, High	54	49	49	54
Multi-Material, Low	57	52	52	57
Newsprint, High	60	54	54	60
Newsprint, Low	63	58	58	63
Beverage Containers	65	59	59	65

EXHIBIT 7
OVERALL ENERGY BALANCE

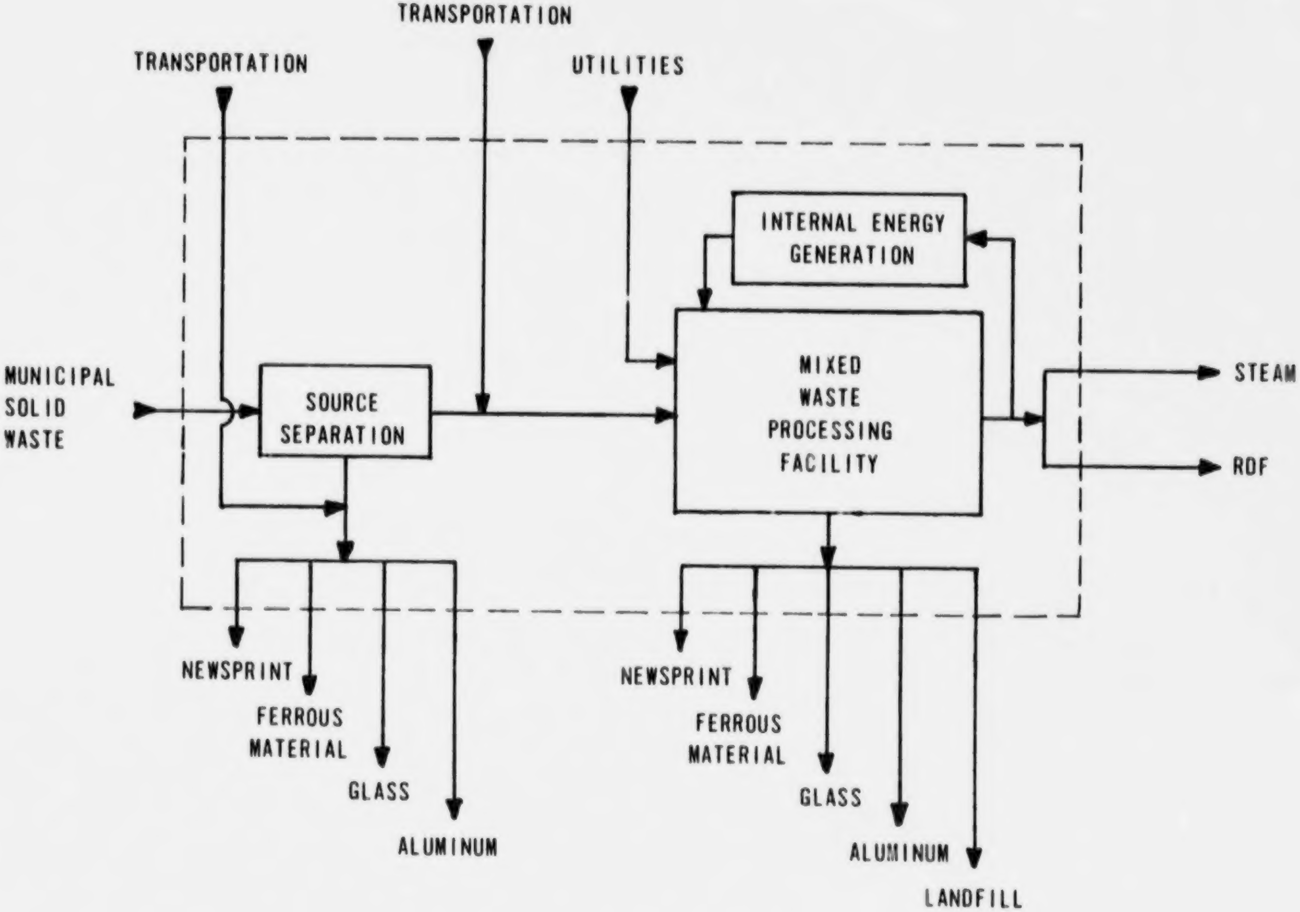

TRANSPORTATION
TRANSPORTATION
UTILITIES
INTERNAL ENERGY GENERATION
MUNICIPAL SOLID WASTE
SOURCE SEPARATION
MIXED WASTE PROCESSING FACILITY
STEAM
RDF
NEWSPRINT
FERROUS MATERIAL
GLASS
ALUMINUM
NEWSPRINT
FERROUS MATERIAL
GLASS
ALUMINUM
LANDFILL

EXHIBIT 8

ENERGY CONSERVATION - NET ENERGY RECOVERY EFFICIENCY, %
(Fixed or Expanded Service Area)

	Mixed Waste Processing Alternative			
Source Separation Scenario:	UWCF	PWCF	RDFF	MI
Multi-Material, High	70	65	65	65
Multi-Material, Low	67	63	63	61
Newsprint, High	68	62	62	61
Newsprint, Low	69	64	64	61
Beverage Containers	73	67	67	67

EXHIBIT 9

ENVIRONMENTAL EFFECTS - RESIDUALS TO LANDFILL,
(tons/day for 1,000 tons of mixed waste generated)

	Mixed Waste Processing Alternative			
Source Separation Scenario:	UWCF	PWCF	RDFF	MI
Multi-Material, High	135	135	135	161
Multi-Material, Low	171	171	171	208
Newsprint, High	196	196	196	238
Newsprint, Low	196	196	196	238
Beverage Containers	147	147	147	180

EXHIBIT 10

ENVIRONMENTAL EFFECTS - EMISSIONS TO AIR, TONS/DAY FOR 1,000 TONS OF MIXED WASTE GENERATED

		Mixed Waste Processing Alternative			
Source Separation Scenario:		UWCF	PWCF	RDFF	MI
Multi-Material, High	(a)	1.51	0.50	0.47	1.25
	(b)	0.42	2.57	2.57	1.62
	(c)	1.16	1.06	1.00	1.08
	(d)	0.03	1.12	1.25	1.12
Multi-Material, Low	(a)	1.60	0.53	0.49	1.32
	(b)	0.45	2.71	2.71	1.71
	(c)	1.23	1.23	1.05	1.14
	(d)	0.04	1.19	1.32	1.19
Newsprint, High	(a)	1.68	0.55	0.52	1.38
	(b)	0.47	2.69	2.69	1.80
	(c)	1.29	1.29	1.11	1.20
	(d)	0.04	1.24	1.38	1.24
Newsprint, Low	(a)	1.77	0.58	0.55	1.46
	(b)	0.50	2.76	2.76	1.90
	(c)	1.36	1.36	1.17	1.27
	(d)	0.04	1.31	1.46	1.31
Beverage Containers	(a)	1.82	0.60	0.56	1.50
	(b)	0.51	2.80	2.80	1.95
	(c)	1.40	1.40	1.20	1.30
	(d)	0.04	1.35	1.50	1.35

(a) Particulates
(b) SO_2
(c) NO_x
(d) Hydrocarbons

EXHIBIT 11

ECONOMIC EFFECTS - DISPOSAL COST, $/TON OF MIXED WASTE GENERATED

(Fixed Service Area)

	Mixed Waste Processing Alternative			
Source Separation Scenario:	UWCF	PWCF	RDFF	MI
Multi-Material, High	26.3	39.0	39.0	42.3
Multi-Material, Low	27.3	40.1	40.1	44.1
Newsprint, High	28.6	41.6	41.6	45.9
Newsprint, Low	28.8	42.0	42.0	46.4
Beverage Containers	27.7	41.5	41.5	45.3

EXHIBIT 12

ECONOMIC EFFECTS - DISPOSAL COST, $/TON OF MIXED WASTE GENERATED

(Expanded Service Area)

Source Separation Scenario:	Mixed Waste Processing Alternative UWCF	PWCF	RDFF	MI
Multi-Material, High	26.1	38.6	38.6	42.2
Multi-Material, Low	27.2	39.8	39.8	44.1
Newsprint, High	28.6	41.1	41.1	45.9
Newsprint, Low	28.8	42.0	42.0	46.5
Beverage Containers	27.8	41.5	41.5	45.3

FORECASTS OF THE QUANTITY AND COMPOSITION OF SOLID WASTE

Ralph M. Doggett
International Research and Technology Corporation
McLean, Virginia 22102

Andrea L. Watson
Bechtel Corporation
San Francisco, California 94119

ABSTRACT

Five scenarios of future solid waste generation have been developed using a methodology linked to an interindustry forecasting model. The estimated quantity and composition of solid waste in the future is affected by key model parameters. The purpose of this paper is to indicate the impacts of technology change, materials substitution, resource recovery initiatives, and average product lifetime on the solid waste load within the context of the model. The forecasts are made for the year 1990.

INTRODUCTION

Factors affecting the quantity and composition of future solid waste streams include technology change, materials substitution, product lifetimes and the extent of resource recovery. These considerations are the basis of five scenarios of future solid waste generation that have been developed using an interindustry forecasting model of the U.S. economy. The economic model referred to here is the Interindustry Forecasting Model of the University of Maryland (INFORUM).

The starting point for the analysis is a data base of historical material flows, for each of 14 materials to 21 product categories. Each product category has an estimated average lifetime, after which the product enters the waste stream. Prompt scrap and other diversions are accounted for, as is the extent of recycling. In the forecast mode, the data base is linked to the economic forecasting model, which employs an input-output table to estimate the future demands for each product, and the flows of materials to these products, out to the year 1990.

In this paper, the assumptions and results of each of five scenarios are presented, beginning with a reference case, or business-as-usual scenario, and followed by discussions of scenarios in which key parameters affecting technology change, materials substitution, product lifetime and resource recovery, have been changed.

THE REFERENCE SCENARIO

An economic growth scenario that includes a continuation of historical and current trends in technology change and materials substitution, serves as a reference case for our analysis. The economy, represented by real Gross National Product, grows at a long-term average rate of 3.4 percent per year, while population growth slows to 0.9 percent per year over the forecast period. The scenario incorporates a significant amount of materials substitution by industry. Most notably, transportation equipment manufacturers are projected to use significant amounts of aluminum and plastics in place of steel. Glass and steel are largely replaced by plastics, paper and aluminum in the beverage containers industry, and more and more plastics replace paper in packaging.

Recycling rates for 1990, as shown in Table 1, are fairly optimistic; 29 percent of all paper entering the waste stream is recycled, 58 percent of the aluminum, 62 percent of the steel, and 6

TABLE 1. REFERENCE SCENARIO, POST-CONSUMER RECYCLING ASSUMPTIONS(1) 1971 and 1990

Material	Percent Recovered 1971	Percent Recovered 1990
Paper and Paperboard	23.2	29.0
Glass	9.9	12.3
Metal	52.5	61.1
Ferrous	52.8	61.8
Aluminum	44.8	57.6
Other	51.1	61.3
Plastics	6.7	5.9
Rubber and Leather	5.0	9.5
Textiles	56.7	54.3
Wood	18.8	21.2
Concrete	0.0	0.0
Total Non-Food	27.7	28.3
Food Waste	0.0	0.0
Total Product Waste	25.6	26.7
Yard Waste	0.0	0.0
TOTAL	23.7	24.9

(1) The figures presented here are composites for materials recovered from 21 different product categories.

Source: Compiled by International Research and Technology Corporation.

percent of plastics. The high amounts of aluminum and steel are recovered primarily from automobiles.

Note that the figures presented in Table 1 are composites for materials recovered from 21 different product categories. For example, it is assumed that 95% of the steel in automobiles scrapped in 1990 will be recovered, while only 25% of the steel in household durables will be recovered.

Average product lifetimes assumed for each of the 21 product categories are presented in Table 2. Six of the product categories have assumed average lifetimes of less than a year. These include newspapers, disposables, and beverage containers. Automobiles, furniture and household durables are assumed to last an average of ten years, while structures last an average of fifty years before demolition.

The historical materials flow data base, and the prompt scrap, diversions, recycling and average product lifetime assumptions, are all combined with projections by the economic forecasting model to estimate the future quantity and composition of solid waste.

Results for the reference scenario are presented in Table 3. As can be seen, high growth rates are projected for net waste generation of aluminum and plastics, while the amount of steel in the waste stream increases very slowly. This is largely the result of substitutions in the automobile industry, suggested earlier. Similarly, wood wastes are projected to grow slowly, as a result of high substitutions of concrete for wood in construction over the past thirty years. The fairly rapid growth in the amounts of rubber, leather and textiles in the waste stream reflects production trends of

TABLE 2. REFERENCE SCENARIO. AVERAGE PRODUCT LIFETIME ASSUMPTIONS (YEARS

Product Category	Average Lifetime	Product Category	Average Lifetime
Newspapers	< 1	Electrical/Electronics	15
Books and Periodicals	< 1	Machinery	20
Writing Paper	< 1	Automobiles	10
Disposables	< 1	Other Transp. Equipment	20
Beverage Containers	< 1	Tires	5
Other Packaging	< 1	Batteries	3
Consumer and Inst. Products	7	Construction	50
Furniture	10	Ordnance	5
Apparel	4	Other Industrial Applications	2
Footwear	2	Miscellaneous	5
Household Durables	10		

Source: Compiled by International Research and Technology Corporation.

TABLE 3. REFERENCE SCENARIO. PROJECTIONS OF NET SOLID WASTE FROM ALL SECTORS, 1971 AND 1990(1) (Million Metric Tons Except as Noted)

Material	1971	1990	Avge. Annual Percentage Growth
Paper and Paperboard	35.10	53.09	2.20
Glass	10.98	18.54	2.80
Metal	38.26	41.84	0.47
Ferrous	(35.02)	(36.87)	.27
Aluminum	(1.17)	(2.39)	3.83
Other	(2.07)	(2.58)	1.17
Plastics	3.22	10.24	6.28
Rubber and Leather	2.28	5.13	4.36
Textiles	1.38	3.48	4.99
Wood	31.69	37.32	.86
Concrete	43.02	101.15	4.60
Total Non-Food Products	165.93	270.83	2.61
Food Waste	18.68	22.10	.89
Total Product Waste	184.61	292.93	2.46
Yard Waste	20.38	29.84	2.03
TOTAL	204.99	322.78	2.42
Tons per $1,000 GNP	.19	.16	-0.90
Lbs. per capita/day	5.97	7.91	1.49

(1) Includes Residential, Commercial, Industrial, Automotive and Other Transportation, Construction and Demolition Wastes. Excludes Agricultural and Mining Wastes.
Source: International Research and Technology Corporation.

the past decade, during which the output of these materials increased almost 70 percent.

The total net waste load grows at a rate that is significantly lower than that of real Gross National Product. Consequently, the quantity of waste per dollar of GNP is projected to decline at just under a percentage point per year through 1990. However, the net solid waste load per capita is estimated to increase slowly, from just under six pounds per person per day, to almost eight pounds per person per day, while per capita GNP grows at 2.5 percent per year.

TECHNOLOGY FREEZE

Projections of total net solid waste in 1990 are dramatically different given the assumptions of four alternative scenarios. These projections are compared in Table 4. The first alternative scenario, which we have called Technology Freeze, uses the economic projection of the Reference Scenario, except that there is no substitution of materials in the production of goods, and there is no technology change. However, the prompt scrap, recycling and product lifetime assumptions used in the reference scenario were maintained. As would be expected, the amounts of paper, glass, steel, and wood are greater in the Technology Freeze scenario, while the amounts of aluminum and plastic are less. Food and yard waste projections were held constant between scenarios (the same population projections are employed), and the concrete estimates are the same since this waste comes from structures erected prior to 1971. The effect of the

TABLE 4. COMPARISON OF NET SOLID WASTE PROJECTIONS FOR 1990
(Million Metric Tons Except as Noted)

Material	Reference Scenario	Technology Freeze	Constant Recycling	Increased Recycling	Increased Product Life
Paper and Paperboard	53.10	60.47	56.49	51.66	52.81
Glass	18.54	23.53	18.97	18.46	18.18
Metal	41.84	46.46	53.51	39.11	36.28
Ferrous	(36.87)	(41.74)	(47.64)	(34.61)	(31.50)
Aluminum	(2.39)	(2.03)	(2.96)	(2.24)	(2.31)
Other	(2.58)	(2.70)	(2.91)	(2.26)	(2.47)
Plastics	10.27	8.01	10.27	10.27	9.80
Rubber and Leather	5.13	4.81	5.28	5.08	5.00
Textiles	3.48	3.68	3.48	3.11	3.39
Wood	37.32	40.53	37.32	37.32	36.35
Concrete	101.15	101.15	101.15	101.15	80.77
Total Non-Food Products	270.83	288.64	286.48	266.16	242.60
Food Waste	22.10	22.10	22.10	22.10	22.10
Total Product Waste	292.93	310.74	308.58	288.26	264.70
Yard Waste	29.84	29.84	29.84	29.84	29.84
TOTAL	322.77	340.57	338.41	318.10	294.53
Tons per $1,000 GNP	.19	.20	.20	.19	.17
Lbs. per capita per day	5.97	6.30	6.26	5.88	5.45

Source: International Research and Technology Corporation.

Technology Freeze scenario assumptions on the total net solid waste projection is an additional 18 million tons by 1990, an increase of 5.5% over the Reference Scenario projection. The materials substitution assumptions of the Reference Scenario have heavier materials being replaced with lighter materials, therefore resulting in the smaller waste load.

IMPACTS OF RECYCLING

For two of the alternate scenarios, variations in the recycling assumptions have been incorporated. Both alternates employ the technology change, materials substitution, prompt scrap, and product life assumptions of the Reference Scenario. However, one scenario, called Constant Recycling, has no change from the recycling rates assumed for 1977, and the other, called Increased Recycling, reflects an assumed 10% increase in the recycling rates for all materials from all products and for all forecast years, over the rates assumed in the Reference Scenario. These recycling assumptions are applied at the point of disposal; the prompt scrap and other diversion rates were not changed.

The results suggest that the greatest post-consumer resource recovery potential lies with metals. The amount of unrecycled metal in the 1990 waste load is over 11 million metric tons higher in the Constant Recycling scenario than in the Reference Scenario, a difference of 28 percent. Again, automobiles account for the bulk of this difference: the fraction of aluminum recovered from junked automobiles is assumed to double in the Reference Scenario, from 30 percent in 1971 to 60 percent in 1990. In the Constant Recycling Scenario, only 39% of the aluminum from automobiles scrapped in 1990 is recovered. Similarly, 85 percent of the steel contained in automobiles scrapped in 1971 was recovered. This fraction increases to 95 percent by 1990 in the Reference Scenario. However, in the Constant Recycling Scenario, the fraction remains at 88% from 1977 on. The impact on the total net waste load is a projection that is 15.6 million tons greater than that of the Reference Scenario, a difference of 4.8 percent.

In the Increased Recycling Scenario, the change is less dramatic, but still significant. The difference in the 1990 net waste load projection is only 1.4 percent, but the amounts of steel, aluminum, other metals and textiles are 6 to 12 percent lower than the amounts in the Reference Scenario projection.

INCREASED PRODUCT LIFE

The lowest net solid waste projection is found in the Increased Product Life Scenario. For this projection, the assumed average product lifetime was increased 10% for all products listed in Table 2 that have average lifetimes of over one year. All other assumptions of the Reference Scenario were maintained. The impact is greatest on the projections of steel and concrete, materials that are typically used in products with especially long average lifetimes. The differences in the projections for these two materials alone account for over 90 percent of the total difference between scenarios. For all other materials, the differences are less than 5 percent, since they are typically incorporated in products with comparably short average lifetimes.

SUMMARY AND CONCLUSIONS

The five scenarios presented above depict a range of plausible future net solid waste loads. The estimates for 1990 vary from a total of 295 million metric tons assuming increased product lifetimes, to 341 million tons assuming an absence of technology change and materials substitution. The projected trends in post-consumer recycling initiatives can reduce the 1990 net waste load by 5 percent, and a modest increase in these initiatives can reduce the load an additional 1 percent, for a total reduction of 20 million metric tons by 1990. It is clear that the extent of technology change and materials substitution, the effectiveness of recycling initiatives, and the average lifetimes of future products, can substantially affect the quantity and composition of the waste generated by our society.

THE DEVELOPMENT OF TESTING AND ANALYSIS PROCEDURES FOR REFUSE-DERIVED FUEL

Dr. John Love, Jr.
Professor of Mechanical and Aerospace Engineering
University of Missouri-Columbia
Columbia, Missouri 65211

Mr. Carlton C. Wiles
U.S. Environmental Protection Agency
Municipal Environmental Research Laboratory
26 West St. Clair St.
Cincinnati, Ohio 54268

ABSTRACT

When procedures have not been standardized or are not readily available, establishment of meaningful purchase-sales agreements often become a barrier between user and producer. The success of RDF resource recovery systems will depend upon the ability to market the RDF at a price that reflects its true value. Current reluctances to accept RDF still relate to uncertainties concerning its ultimate effects on boiler surfaces and associated equipment such as materials handling systems and a general suspicion, perhaps, that it is an inferior fuel. While there are some bases for caution, some of the problem relates to the inability of a user and producer to agree to procedures that will establish the key characteristics of the fuel. If these procedures can be developed and standardized, it not only will provide the basis for sound purchase-sales contracts, but will also help to better define what RDF is and what it has to offer compared to other fuels. The following paper describes the efforts of ASTM Subcommittee E38.01 Energy in developing consensus standards for characterization of a specially processed refuse-derived fuel, RDF-3.

INTRODUCTION

Various industries have practiced the reuse and recycling of their residual materials for a long time and these wastes of production are becoming a more important source of raw material for their products, by-products, or as supplemental fuel as energy costs continue to rise. The materials reused by manufacturers do not get into a general waste stream, and thus the characteristics of the scrap are generally well known.

In the early sixties when formal collection of mixed solid waste from households was begun by municipalities, because it was no longer feasible for the individual to dispose of his own waste as he saw fit, it was used as land fill. It was obvious that several components of the waste had some commercial value if separated and precisely identified. Various non-profit groups found it advantageous to recover the cans, bottles, and newspapers for recycling. In general this was accomplished at the source, by cajoling those generating the waste to separate their waste and deliver it to collection centers, as a civic duty. However, it is unlikely that separation at the source, though highly desirable and economical, will predominate in the recovery of all the components in MSW which have a commercial value. The major portion of municipal solid waste collected is a complicated mixture requiring considerable processing to recover the commercially valuable components that must be precisely identified. At some point the cost of separation exceeds the value of the recovered fractions; the remainder, if it can be properly characterized, is suitable for use as a fuel.

The obvious need to study the problem of deposition of Municipal Solid Waste led to the formation, through the efforts of Dr. Harvey Alter, of the National Center for Resource Recovery, of ASTM Committee E38.00 on Resource Recovery. The scope of this committee is as follows: "The development of methods of test, specifications, recommended practices, and nomenclature; the promotion of knowledge, and stimulation of research relating to material and energy resources, recoverable, or potentially recoverable, from waste. The waste for resource recovery is here defined as that portion of waste which is collected from industrial, commercial,or households destined for disposal facilities."

The American Society for Testing and Materials, ASTM, is a non-profit corporation "formed for the development of standards on characteristics and performance of materials,products, systems, and services; and the promotion of related knowledge." It is essentially a management system for development of voluntary consensus standards through its standards committees. The membership of each committee must be a designated balance between users, producers, and general interest groups concerned with the proposed standard. ASTM procedures insure that its standards are the result of a full consensus of its members by submitting them to a society letter ballot before publication. ASTM standards are nonmandatory and only become true standards when accepted by the interested parties, or are adopted by an industry or governmental body by law. ASTM provides no funds for the operation of its committees; all the work is done voluntarily by the members.

ASTM COMMITTEE E38 ON RESOURCE RECOVERY

The committee became fully operational in April, 1974, when twelve subcommittees were given the responsibility for development of standards relating to a specific use or fraction of mixed municipal solid waste. In addition to the executive subcommittee, E38.90, the following subcommittees are promulgating standards:

E38.01 Energy
.02 Ferrous Metals
.03 Non-Ferrous Metals
.04 Paper and Paperboard
.05 Glass
.06 Construction Materials
.07 Health and Safety
.08 Unit Processes
.09 Terminology

In addition there are subcommittees for Research and Long Range Planning. The subject of this paper is confined to the activities of Subcommittee E38.01 Energy.

ASTM SUBCOMMITTEE E38.01 ENERGY

Dr. John Love, Jr., Professor of Mechanical and Aerospace Engineering, University of Missouri-Columbia, was appointed chairman of the subcommittee in the spring of 1973. The first year was spent in trying to determine the scope of the subcommittee and finding members with experience and/or expertise in using Municipal Solid Waste as a commercial product. Fortunately about forty interested members attended the first productive meeting in April, 1974. The scope approved by the main committee is as follows: "The identification of and the development of nomenclature, standards, specifications, methods of test and recommended practices relating to the recovery of energy or fuels and/or organic feed stocks from waste; the promotion of knowledge, and stimulation of research relating to direct or indirect conversion into chemical or biological energy forms." Waste was defined as above. Two full days of discussion uncovered what seemed to be an infinite number of problems and suggestions of what to do with a packer truck of MSW of unknown composition. However, the subcommittee soon divided itself into two major groups: those in favor of biological and/or pyrolitic conversion into chemical feed stocks and those in favor of direct conversion by using the waste as a fuel. Regardless of the ultimate use of MSW it must be completely characterized by its physical and thermo-chemical properties, if it is to become a commercial product, and a reliable sampling technique must be developed to insure the laboratory sample is representative of a given lot of the material. The subcommittee began work on writing initial specifications for the product, sampling, and analysis of refuse-derived fuels and/or chemical feed stocks.

DEFINING THE PROBLEM

The useful products likely to be recovered from mixed municipal waste are paper, steel, aluminum, glass and a residue of mixed organic materials that may be used as a fuel or chemical feed stock. A refuse-derived fuel or chemical feed stock in the broadest sense may be the raw waste as-collected; the as-collected waste processed to a coarse particle size with or without the removal of glass and ferrous metals; or the combustible waste fraction from which all or most of the inorganic material has been removed, the organic residue. The combustible waste fraction may be further processed into powdered, pelletized, liquid, or gaseous fuels.

From the possible forms of refuse-derived fuels the subcommittee chose to characterize the combustible waste fraction as this would meet the requirements of those interested in both indirect and direct conversion. Impetus was given to this decision by the fact that Milwaukee and Chicago were building processing plants to produce this type of fuel for consumption in utility boilers, and contractual agreements required quality and quantitative specifications. This form of refuse-derived fuel has been tentatively designated by E38.01 as RDF-3, defined as a light-weight, shredded material passing through a two-inch screen which has been density-classified with most of the inorganic material removed.

The task groups found some thirty-seven characteristics relating to RDF-3 as a product for direct conversion fuel. Eventually these were listed in order of priority; of course, sampling was number one on the list, with physical and thermochemical properties following. The task groups were assigned to write draft standards for those parameters with a high priority. Although most of the subcommittee members had little or no experience in using RDF-3 as a fuel, nearly all of them were potential users or producers associated with fuel laboratories and were familiar with the ASTM standards for coal and coke. The first draft standards followed the established ASTM standards for coal and coke closely with minor changes based on the thoughts of the authors, who at this time were managers of utility laboratories. Needless to say, these drafts were thoroughly challenged as no experimental evidence could be cited to support them, and the subcommittee became completely bogged down in endless debate over the details of the draft standards. Obviously a closely controlled interlaboratory study, known as a Round Robin, was the most effective means of determining the validity of the details of the proposed draft standards. However, the committee had no funds for such a program.

The lack of acceptable standards for determining the value of RDF-3, between the user and producer, is a formidable barrier to the general use of it as fuel. EPA recognized that the most expeditious and effective way to remove this barrier was to assist subcommittee E38.01 in the development and testing of its proposed standards arrived at through the consensus approach of ASTM. EPA-Solid and Hazardous Waste Research in Resource Recovery Division is therefore cooperating with ASTM by providing support funding for the subcommittee's effort. Mr. Carlton Wiles, second author, is Project Manager for EPA, with the Chairman of E38.01 as Principal Investigator.

An advisory group composed of one potential user, two producers, and two general interest members was formed by the Principal Investigator to assist in determining the priorities for the interlaboratory study and the general area the investigation should include. It was agreed that sampling procedures were undoubtedly the most important, but it was soon discovered that without acceptable standards for determining the physical and thermochemical parameters of the material there was no way to differentiate between sampling procedures. Thus the sampling study will follow the present study.

The problem finally defined was as follows: develop and test, by Round Robin procedures, draft standards for the parameters included in (a) size distribution determination; (b) modified proximate analysis; (c) modified ultimate analysis; and (d) ash fusion analysis.

The parameters included in the various analyses by definition are:

(a) Size distribution: Results of a sieve analysis of the air-dried sample.

(b) Modified proximate analysis:

1. Total moisture
2. Residual moisture
3. Higher heating value on an as received, moisture free, and moisture and ash free basis
4. Sulfur
5. Total chlorine
6. Water soluable chloride
7. Ash
8. Volatile matter

(c) Modified ultimate analysis:

1. Total moisture
2. Residual moisture
3. Carbon
4. Hydrogen
5. Nitrogen
6. Oxygen

(d) Ash fusion analysis:

1. Initial deformation
2. Softening
3. Hemispherical
4. Fluid temperatures in both an oxidizing and reducing atmosphere

THE EXPERIMENTAL PROGRAM

The objective of the experimental program is to perfect the protocols used in the draft standards and to determine for each a precision statement for the results by stating the limits of Repeatability (duplicate results by the same laboratory on different days) and Reproducibility (results submitted by different laboratories).

The initial steps of setting up an inter-laboratory Round Robin program for a "new" product such as RDF-3 are formidable. The precise method of testing must be determined, a source of uniform representative samples found, and a list of willing and able laboratories must be developed. It was decided that the method of testing would follow ASTM E-180, Standard Recommended Practice for "Developing Precision Data on ASTM Methods for Analysis and Testing of Industrial Chemicals." The procedures described in this document are very precise and it states that "Each analyst is required to perform duplicate determinations on each sample on each of two days---." Thus four separate analyses of a given parameter constitute a "Round". Some eighteen laboratories were selected from the utility, governmental, and commercial sectors in keeping with the spirit of the consensus approach. These laboratories were widely separated geographically.

Since RDF-3 is made up of the organic fraction of MSW including kitchen waste, the question was raised as to amount of decomposition, off-gassing, and loss of moisture that could occur during shipping that could affect the analysis. To answer this question, National Center for Resource Recovery prepared seven two kilogram samples of RDF-3 for shipment to the most remote (shipping time) laboratory. All of the samples were double bagged in three mil plastic bags securely sealed. Two of the samples were packed with dry ice in insulated cartons; thermocouple leads were brought outside the cartons so that the temperature could be monitored without opening. One of these two samples (the control) was shipped by air freight, the other by UPS. The control sample was analyzed when it reached the freezing temperature. The other five samples were shipped "hot" in uninsulated cartons by UPS. One of these five samples, containing a maximum-minimum thermometer, was opened and analyzed immediately, the others were stored at 100^{o}F and analyzed at approximately 14 day intervals. The Proximate and Ultimate analyses were used to determine if the time and/or temperatures normally encountered during shipping had an effect on the stability of the samples. No significant change was found in the parameters for the control sample and the "hot" samples. RDF-3 samples packed as above can be considered stable for at least eight weeks.

The procedures of E-180 require that all laboratories use the same precise protocol; at this time only four standards had been drafted, it was incorrectly assumed that ASTM Standards for Coal and Coke would be suitable for the remaining parameters. No formal interlaboratory testing had been done to confirm the existing drafts or the

ASTM standards. One draft standard, "Standard Method of Preparing RDF-3 Samples for Analysis", had been used by several utility laboratories to prepare an analysis sample from a gross sample. The procedure described in this draft was widely accepted by the selected laboratories.

Six laboratories (two utility, two governmental, two commercial) were selected to make the pilot studies, or Zeroth Round. No protocols were designated for these initial studies except those given by ASTM standards allowing variations from the standards as the laboratories saw fit, and using available equipment. The laboratories were required to give complete detailed protocols used; suggest "better" and less costly methods, and evaluate their results. The results of the Zeroth Round were extremely disappointing; there was little or no consistency in the results or protocols used. due in part to the poor sample received, but also due to inexperience with this material, lack of proper equipment, and improvising when equipment was unavailable. A multitude of unforseen problems surfaced, but at least this Round served as a guide to the modifications needed in the procedures. It was decided to run a Second Zeroth Round.

At this juncture, a laboratory advisory group was formed consisting of the representatives from each of the Zeroth Round participants to assist the Principal Investigatorin planning the Second Zeroth Round and administration of the larger problem to come when the subsequent Round Robins were run. This group met in December, 1977. The meeting was very productive. The problems encountered in the Zeroth Round were thoroughly examined; it was agreed that the standard methods and apparatus normally used in coal analysis were not suitable for the characterization of RDF-3. Several of these standards need major modifications. The group agreed to develop these standards for the subcommittee's perusal. However, after considerable discussion it was decided the Second Zeroth Round would be run without specific protocols except that the draft standards for the preparation of the laboratory sample, sieve analysis, and moisture determination would follow the draft standards in process of perfection.

The results of the Second Zeroth Round were promising. The statistical analysis of the results seemed to indicate we were on the right track. The protocol for preparing and shipping the samples was being followed, and several of the laboratories followed the new draft standards developed by the advisory group. However, several problems still remained, but in particular the normal size of the laboratory analysis sample as well as its homogeneity was questioned. Several laboratories were assigned to do individual experiments to answer these questions and incorporate their findings into the draft standards. Nevertheless the advisory group felt that we had sufficient information to proceed with the first full Round Robin with required protocols. The protocols to be used were from our draft standards, as modified, except for six parameters for which the ASTM coal standards seemed to be appropriate.

The First Round samples were prepared and shipped in June, 1978, to eleven laboratories of which eight responded with results for all the parameters. The statistical analysis of the results indicated that the laboratories had obtained better repeatability in their analyses, but the reproducibility, that is, between laboratories, had not been achieved. These results were not in an acceptable range that could be used as a basis for precision statements. The advisory group reviewed the precise protocols used and the new problems uncovered, they produced new draft standards for the problem areas as well as modified those already in use where difficulties were encountered. However, we were well enough along to run the Second Round Robin.

The Second Round samples were prepared and shipped by NCRR early in December, 1978. A second representative laboratory sample, dry passing through a ½ mm screen, was prepared by one of the laboratories for shipment to all participants for cross-checking the reproducibility between laboratories, and to eliminate as far as possible the non-uniformity of samples shipped by NCRR. The protocols to be used by all thirteen laboratories participating in the Second Round are from our latest draft standards except those for volatile matter, carbon, hydrogen, and nitrogen. The ASTM coal standard for these parameters are thought to be suitable. The results of this Round are due to be returned February 1, 1979, some four weeks after this date. It is hoped that the results will be adequate to determine the precision statements, if not the draft standards will be further modified for the Third Round.

The details of the laboratory protocols are described in the most recent Draft Standards (see Appendix A). As these drafts are subject to reivision at any time when new problems surface, they are not available for general use.

ORGANIZATION OF THE SUBCOMMITTEE

The E38.01 Energy subcommittee has about sixty-five members. It is divided into nine Task Groups, each with a new leader who is responsible for the Draft Standards relating to his general scope. The members of these groups are engineers, scientists, educators, and managers, who are extremely interested and dedicated to using MSW as a source of energy; their work is voluntary and contributed to the subcommittee on their own time and at their own expense. The major effort, at present, is to establish RDF-3 as a commercially competative fuel, by providing a set of standards that will characterize it by its physical and thermo-chemical properties.

The broad interest of the subcommittee is indicated by the scopes of its Task Groups (see Appendix B).

The subcommittee is also supporting some of the work of E38.06 Construction Materials through a subcontract for the "Development of Test Methods and Specifications for Resource-Recovered Glass in Structural Clay Products."

SUMMARY OF ACTIVITIES

At present the major activity and effort of the subcommittee are devoted to the development of precision statements for the Draft Standards for the parameters listed in the four analyses subject to the Round Robin study. It is interesting to note that this does not depend upon the accuracy of the absolute value found, or a gross sampling technique. Thus as long as the sample prepared by NCRR is representative of the particular lot of RDF-3 from which it was taken, the Round Robin results are valid. The uniformity of the samples is being checked, as stated above, in the Second Round Robin. This is not to say the handling, subdivision, and homogeneity of the laboratory sample is not important, in fact, the Round Robin procedure will determine the protocol to be used. Note, the accuracy of the analytical determination can only be determined for a material of known composition.

The subcommittee has developed a Draft Standard for Recommended Practice for Describing the Properties of Pyrolitic Fuels. It is expected to be resubmitted to the main committee for a letter ballot in the near future. This standard has not been the subject of a Round Robin.

The collection and division of a gross sample is also being studied by one of the Task Groups.

The protocols for a detailed analysis of the desirable parameters are time consuming and expensive, and although valuable and necessary for determination of the true commercial value of RDF-3 delivered over a long period, usually a thirty-day average for fossil fuels, they are not useful for an ongoing day-to-day quality control program. Through the study of hundreds of analyses of MSW in the literature, it has been found, by one of the Task Groups (Macro-sampling), that if the moisture and ash are known for a lot of material the higher heating value can be estimated to perhaps a commercially acceptable range. Tests are underway to determine the proper, if any, correlations. The proposed procedure is simple; the sample is first dried to a constant weight, then it is reduced to ash. The only equipment required is an oven with the proper temperature control. The subcommittee has tentatively labeled this process Macro-sampling Technique.

The Macro-sampling Technique is not intended to replace the detailed analysis, in fact the correlation depends upon it, but only to give a rapid indication of the quality of the RDF-3 delivered on a short time basis. It could also serve as a contractural parameter for those locations not equipped to perform the detailed analysis.

FUTURE ACTIVITIES

As mentioned above, the development of a procedure for obtaining a statistically sound laboratory sample, say thirty pounds, from a large lot of MSW is indeed a formidable problem. The present sampling methods for coal and coke are not suitable because of the heterogeneous nature of MSW. There is practically no agreement among the subcommittee members how this can be accomplished, or indeed just where in the stream the gross sample should be collected. The various particle sizes of the raw material and the large quantities that must be handled in a commercial operation make quartering, bailing and coring at least unreliable. In short, the procedure of obtaining a statistically sound sample from commercial quantities of MSW must be reliable and inexpensive as the sampling cost could easily exceed the value of the material. Probably automatic collection at some point in a free falling stream is the answer. The collection and division of the gross sample is our next major project.

Other future studies will include the determination of volatile toxicants, metals and trace toxicants in the ash, densification, flowability, storability, retrievability, grindability/friability, abrasiveness, free swelling index, and combustion characteristics such as spontaneous combustion point, ignition point and residence time required for ignition, flash point, and explosiveness.

One other future project is large volume calorimetry in which the subcommittee is cooperating, however, the development work is being done by the National Bureau of Standards.

CONCLUSIONS AND RECOMMENDATIONS

These conclusions and recommendations are those of the Principal Investigator and not necessarily those of Mr. Wiles.

The RDF-3 supplied by NCRR processed from MSW collected in Washington, D.C. can be characterized, on an as-received basis, as a material passing a one-inch screen with a higher heating value of 5000 to 6000 BTU/pound mass, with other parameters as follows: Moisture 17%, Volatile Matter 30%, Ash 16%, Carbon 20%, Hydrogen 2%, Nitrogen 1%, Oxygen 12%, Sulphur .1%, and Chlorine .4%. These values are only approximate and have little value except to show that RDF-3 is certainly suitable as a high quality fuel with a modest heating value. Certainly it is valuable as a commercial fuel.

I believe the subcommittee, even with the associated frustrations, will develop the required Draft Standards, and the ASTM consensus approach is the proper way to develop commercial standards acceptable to both the producers and users of a "new" product, RDF-3. Also although very time consuming, the use of dedicated volunteers in developing the Draft Standards will assure their acceptance by ASTM for publication.

At this time, it appears that the usual small, 1 g, analysis sample is suitable for the thermo-chemical analysis if it is truly representative of the lot.

I recommend that government agencies requiring acceptable standards and procedures help develop them through the ASTM methods by support funding of its committees, as it has done with E38 Resource Recovery, and that EPA extend its commitment to cover the future work of E38.01 Energy.

ACKNOWLEDGEMENT

It is impossible to name all those who are contributing to the work of the subcommittee, however, I am especially indebted to the following: ASTM headquarters and Mr. Sam Bowman, Staff Representative; Dr. Harvey Alter, NCRR, for appointing me as Principal Investigator; the Advisory Group, Dr. Mark T. Atwood, Tosco Corp.; Dr. Jerome F. Collins, DOE; Mr. Herbert I. Hollander, Gilbert Assoc.; Mr. David L. Klumb, Union Electric Co.; Dr. William L. Young, Americology; and the Laboratory Advisory Group, Mr. Richard S. Alberg, Wisc. Elec. Power Co.; Mr. J.E. Attrill, Oak Ridge Nat. Lab.; Mr. Robert Berkemeyer, Williams Bros. Proc. Serv; Mr. Richard R. Dlesk, Commonwealth Edison Co.; Mr. John K. Kieffer, Gilbert Assoc.; and Mr. David J. Mitchell, NBS. Since March, 1977, the work upon which this publication is based was performed persuant to Contract No. 68-03-2528 with the Environmental Protection Agency. Mr. Carlton Wiles is the Project Officer.

APPENDIX

"A"
THE DRAFT STANDARDS PROMULGATED BY SUBCOMMITTEE E38.01 ENERGY TO DATE

1. Standard Recommended Practice for Describing the Properties of Pyrolitic Fuels;
2. Standard Method of Designating RDF-3 from its Sieve Analysis;
3. Standard Method of Preparing RDF-3 Samples for Analysis;
4. Standard Sampling Procedure for RDF-3 Collection and Division of a Gross Sample;
5. Standard Method of Test for Residual Moisture in RDF Analysis Sample;
6. Standard Method of Determining Total Moisture (single stage) in RDF-3 Samples;
7. Test Method for Chlorine in Refuse-Derived Fuel (RDF-3);
8. Standard Test Method for Water-Soluble Chlorides in Refuse-Derived Fuel;
9. Standard Method for Calculating Refuse-Derived Fuel Analysis Data from As-Determined to Different Bases;
10. Test Method for Sulfur in Refuse-Derived Fuel (RDF-3);
11. Standard Method of Test for Ash in the Analysis Sample of Refuse-Derived Fuel (RDF-3);
12. Standard for Determination of RDF-3 Calorific Value by Bomb Calorimeter.

In addition ASTM standards D3175, D3178-73, D3179-73, and D1857 are adopted without change.

"B"
THE TITLES OF THE NINE ACTIVE TASK GROUPS:

1. Macro-Sampling;
2. Gross Sampling;
3. Laboratory Sample Preparation and Proximate Analysis;
4. Thermo-chemical Analysis;
5. Physical Characteristics;
6. Metals and Trace Toxicants in Ash;
7. Pyrolytic Conversion;
8. Large Volume Calorimeter;
9. Evaluation of Energy Recovery Systems.

"C"
THE LABORATORIES PARTICIPATING IN THE SECOND ROUND

1. Commonwealth Edison Co.
2. Rochester Gas and Electric Co.
3. Wisconsin Electric Power Co.
4. National Bureau of Standards
5. U.S. Army Const. Eng. Research Lab.
6. Oak Ridge National Laboratory
7. Foster-Wheeler Development Corp.
8. Combustion-Engineering Power Systems Dept.
9. Gilbert Associates, Inc.
10. Fuel Engineering
11. Williams Bros. Proc. Serv., Inc.
12. Roltech Scientific Services
13. Commercial Testing and Engr. Co.

The first eight laboratories are cooperating in the subcommittee's work gratis. The remainder, commercial laboratories, are billing the subcommittee for reimbursement of only direct cost.

Calorific Value Determination of Refuse-Derived-Fuels by Large-Bomb Calorimetry

Duane R. Kirklin, Eugene S. Domalski and David J. Mitchell

National Bureau of Standards
Washington, DC 20234

ABSTRACT

An oxygen bomb calorimeter has been designed and constructed at the National Bureau of Standards which can accommodate a 25 gram sample of refuse or a refuse-derived-fuel (RDF) for the purpose of studying the effects of sample processing on the measured calorific value. The large calorimeter is an enlarged and modified version of a conventional-sized calorimeter also in use at NBS. The large calorimeter can handle samples ten times larger than the conventional-sized calorimeter and therefore can investigate RDF samples with either minimal or no processing. Calorimetric results are presented on d(densified)-RDF[*] carried out in both calorimetric systems. Moisture- and ash-free (MAF) calorific values were obtained from six randomly chosen unprocessed RDF samples and had a mean value of 10 742 Btu(lb)^{-1} in the large calorimeter. Another randomly chosen analysis sample of unprocessed RDF was subjected to extensive sample processing to obtain a "homogeneous" analysis sample for use in the small conventional-sized calorimeter. Measurement on a set of ten "homogeneous" sub-samples gave a mean calorific value of 10,743 Btu(lb)^{-1} in the small calorimeter. The results of this investigation indicate that the calorific value of d-RDF is unaffected by the sample processing technique used at NBS.

INTRODUCTION

The Resource Conservation and Recovery Act of 1976, PL 94-580, identifies that solid waste is a potential source of oil, gas, or solid fuel which can be converted into energy and mandates that the Department of Commerce provide accurate specifications for recovered materials. The National Bureau of Standards will furnish guidelines, as indicated in this Act, for the development of specifications which pertain to the physical and chemical properties, and characteristics of recovered materials with a view toward replacing virgin materials for various applications.

The heating value is an important characteristic and perhaps the most significant property of a fuel. Heating values are used extensively to evaluate the commercial potential of the fuel and also to evaluate the performance of incinerators and refuse-fired boilers. The E-38 Committee on Resource Recovery of the American Society of Testing Materials (ASTM) is interested in the development of standard methods of test required for the establishment of refuse-derived-fuels (RDF) as an article of commerce. The American Society of Mechanical Engineers (ASME) Performance Test Code 33 Committee is interested in an evaluative method to determine the performance of large incinerators and boilers. A laboratory procedure giving representative and reproducible heating values is necessary to better equip commercial laboratories to certify accurately the energy content of RDF and also to evaluate the compliance of large incinerators and refuse-fired boiler with their contract performance specifications.

---

[*] The d-RDF utilized in this study was produced by Teledyne National in Cockeysville, MD but in no way does this imply an endorsement of this product by the National Bureau of Standards.

A method must be established for precise and accurate determination of the heating value of refuse and RDF to evaluate adequately its fuel value. Therefore, the National Bureau of Standards has entered into a collaborative research agreement with the U.S. Environmental Protection Agency and the U.S. Department of Energy to establish the procedures necessary to determine the calorific value of refuse and RDF by bomb calorimetry. The objectives of this project are to determine the optimum particle size of samples for combustion measurements and to establish whether a conventional (2.5 gram capacity) calorimeter or a larger (25 gram capacity) calorimeter will provide more representative calorific values of RDF. This report provides a response to both objectives from the results obtained for a Teledyne National RDF sample using a conventional (2.5 gram capacity) bomb calorimeter and a recently constructed large (25 gram capacity) bomb calorimeter.

EXPERIMENTAL

Materials

1. Benzoic Acid. Standard Reference Material 39i was obtained from the NBS standard samples storeroom. This sample has a certified energy of combustion of 26 434 ± 3 $J \cdot g^{-1}$ at standard bomb conditions and was used to calibrate the conventional-sized calorimeter. All samples were drawn from the same bottle. Fisher Scientific Company's certified benzoic acid with an energy of combustion of 26 437 ± 3 $J \cdot g^{-1}$ was utilized for the large calorimeter.

2. Oxygen. Ultra High Purity (UHP) grade of oxygen was supplied by Matheson Gas Products. This oxygen is certified to contain combustible impurities not exceeding 0.002 percent and total impurities of less than 0.05 percent.

3. d-RDF. In February 1977, a 20 kg (44 pound) sample of extruded RDF pellets was received from Teledyne National. This laboratory sample was from the Baltimore County Resource Recovery Plant located in Cockeysville, Maryland. The collection of extruded pellets was contained in a plastic bag enclosed in a cardboard box. The Teledyne National pellets are cylindrical in shape having a diameter of 2.5 cm (1 inch) and are broken-off lengths of about 2.5 to 7.5 cm (1 to 3 inches).

Sample Preparation

1. Sample Requirements. It is necessary that a reproducible family of analysis samples be prepared from a gross field sample of refuse or RDF. The analysis sample must be representative of the field sample and unaffected by the laboratory techniques utilized to produce these analysis samples. If it is assumed that the milling and blending of the gross field sample produces a homogeneous product, then the only variational parameter which must be measured and maintained is the moisture content. Therefore, the analysis samples were equilibrated in a constant humidity container at the average relative humidity of the bomb calorimetric laboratory. The temperature and relative humidity of the laboratory are maintained at 295 K and 45 percent, respectively.

2. Small Calorimeter Samples. A random sample of extruded Teledyne National pellets was removed from the field sample of RDF. The preparation of RDF samples for the small calorimeter has already been described [1] and is also provided below. The pellets were ground in a Quaker City Mill (Model 4) to a particle size of less than 1.3 cm (0.5 inch). The particles were then milled to pass a 2 mm (10 mesh) screen in a Wylie Micro-Mill. The ground sample was riffled and then thoroughly blended in a vee blender.

The ground material was then pressed into pellets under a force of approximately 10 000 lbs. Pellets weighed approximately 2.2 grams. These pellets were dried to constant weight at 105 °C in a drying oven and weighed again. The samples were then placed in the constant humidity atmosphere for approximately 48 hours and weighed for a third time.

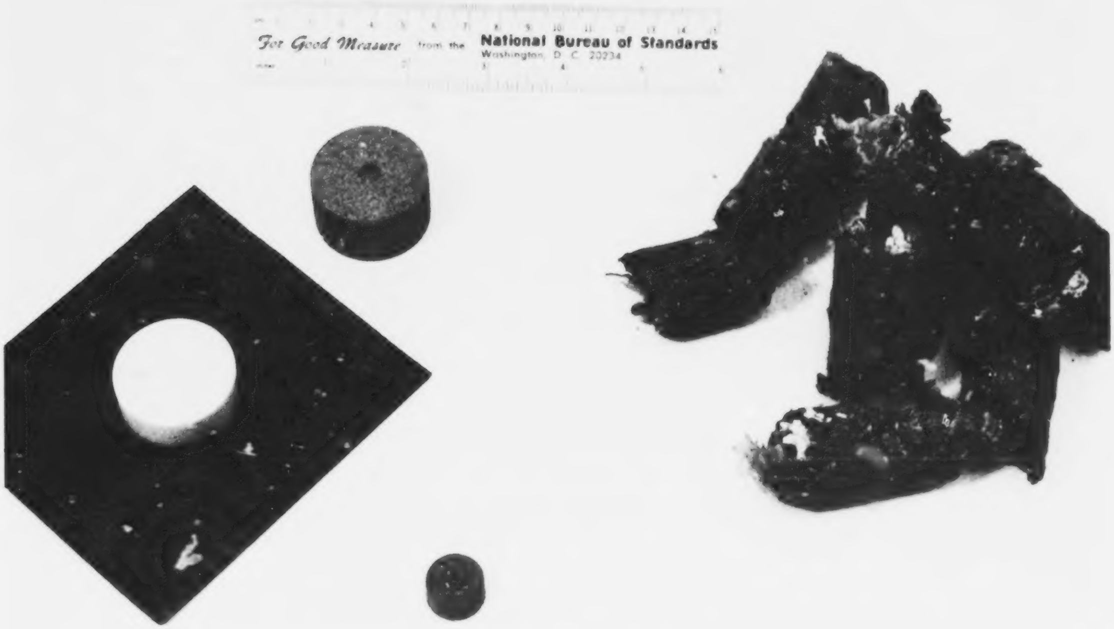
3. Large Calorimeter Samples. Extruded RDF pellets are utilized in the

large calorimeter with no further processing by NBS laboratories. The long extruded pellets were broken into pieces weighing between 20 and 25 grams and placed in a constant humidity atmosphere.

Figure 1 shows the size of a benzoic acid pellets for the large calorimeter, pellets for both the small and large calorimeters, and the unprocessed RDF sample as-received from Teledyne National. The as-received extruded RDF pellets appear heterogeneous while the milled and blended RDF pellets have a more homogeneous appearance.

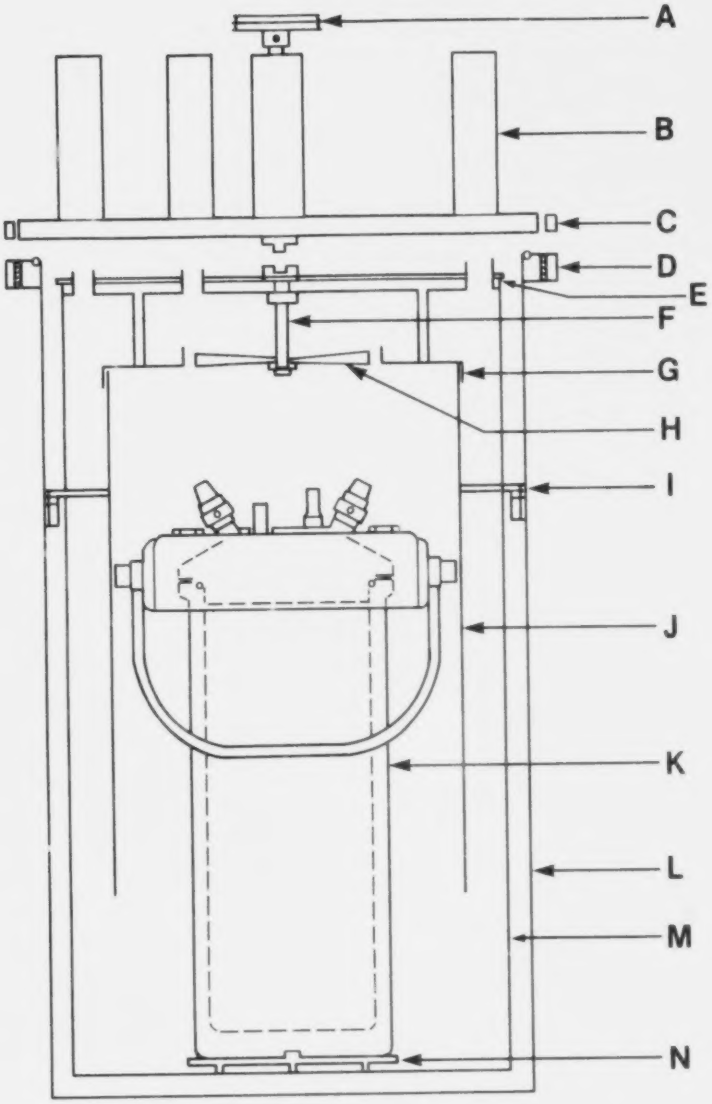
Calorimetric Apparatus

1. Large Isoperibol Bomb Calorimeter. The design of the large isoperibol (isothermal-jacket) calorimeter which will accommodate the large combustion bomb, described in the following section, is similar to that of Coops et al. [2,3] and Gundry et al. [4] and is shown in Figure 2. The calorimeter is constructed entirely on stainless steel. It consists of a cylindrical calorimeter vessel (25.4 cm diam, 45.7 cm height (10 inch diam, 18 inch height)) in which three rods support a concentric cylindrical shield (20.3 cm



Pellets of benzoic acid, processed RDF and unprocessed RDF

Figure 1



25 gram capacity Bomb Calorimeter

A pulley to stirrer motor, B one of four stacks attached to the submarine lid to accommodate (1) fuse circuit, (2) heater, (3) temperature sensor, and (4) pipette, C submarine lid, D submarine flange with "O" ring, E calorimeter vessel lid, F stirrer shaft, G shield cover, H stirrer, I calorimeter vessel supports, J shield, K combustion bomb, L submarine vessel, M calorimeter vessel, N bomb foot.

Figure 2

diam, 30.5 cm height (8 inch diam, 12 inch height)). The calorimeter lid supports a stirrer assembly and a shield cover. The shield, shield cover, and stirrer assembly facilitate the flow of water in the calorimeter so that water is moving (downward) in the space between the bomb and shield, and (upward) between the shield and wall of the calorimeter vessel. The combustion bomb is supported by a foot which has been welded to the bottom of the vessel to insure that the bomb will be positioned in the same manner in the calorimeter for each experiment. The calorimeter vessel contains 19 liters of water for each calorimetric measurement and is housed in a submarine vessel which has a cover. The submarine cover is fastened to the vessel with six bolts and has four vertical ports for: (1) fuse circuit leads, (2) a heater, (3) a central stirrer assembly and, (4) a quartz thermometer. The frequency of oscillation of a temperature sensitive quartz crystal is used to determine the calorimeter temperature. The NBS standard frequencies of 10 and 100 kHz are utilized. The entire calorimeter system (bomb, calorimeter vessel, and submarine compartment) is immersed in a constant temperature water bath maintained at 30 °C to within ± 0.03 °C. The overall volume of the bath is 280 liters and holds 235 liters of water with the calorimeter system immersed in it.

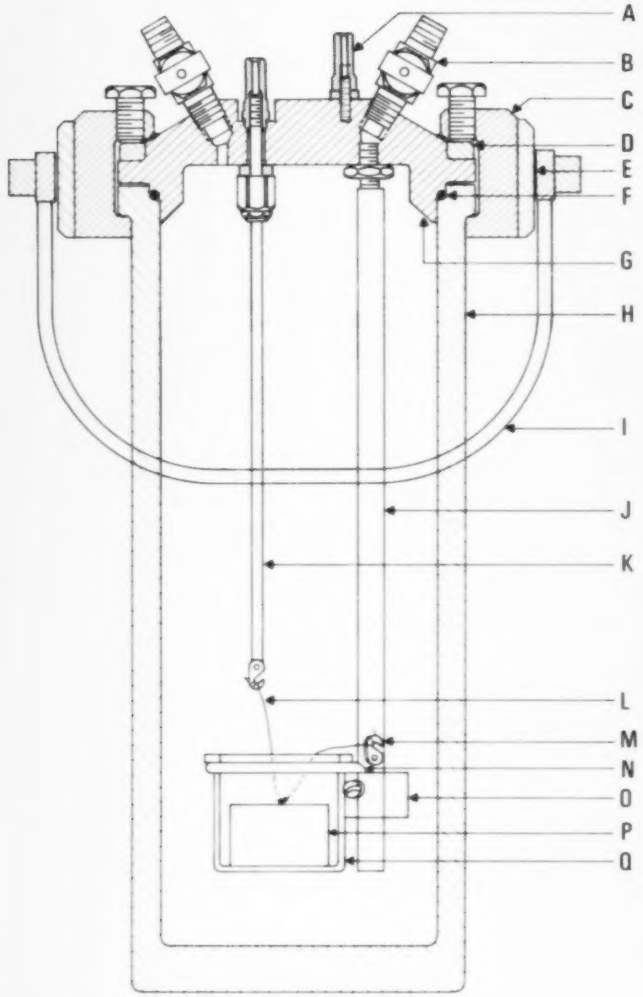
2. Large Combustion Bomb. The combustion bomb which accommodates a 25 gram sample of RDF was purchased from the Parr Instrument Company and is shown schematically in Figure 3. The bomb has an overall height of 35 cm (13.75 in) and has a mass of 13.8 kg (30.5 lb) when assembled; the internal and external volumes of the bomb are 1.85 and 3.62 liters, respectively. A platinum crucible ($\sim$50 cm^3) was used in the calibration experiments with benzoic acid and a stainless steel crucible ($\sim$50 cm^3) was used in the combustion experiments with RDF. The bomb body has a wall thickness of 0.953 cm (0.375 in) and an outer diameter of 11.4 cm (4.5 in).

A photograph of the small and the large combustion bombs is shown in Figure 4 and allows one to examine the relative difference in their sizes. Figure 5 is a photograph of the large calorimeter viewed from the top. It shows the large bomb immersed in the calorimeter vessel with the submarine lid and calorimeter cover (inverted to display the stirrer and shield cover).

Calorimetric Procedure

Bomb calorimetric techniques are well-established and are described in detail elsewhere [5,6], but a brief description of the method used in this work follows. In the thermochemical investigations, the heat evolved by a measured amount of RDF burned is compared with the heat evolved by a measured amount of a selected standard reaction, using a fixed calorimeter system with a specific temperature rise. The standard reaction is the combustion of benzoic acid under standard bomb conditions producing a temperature rise of 3 and 5 degrees in the small and large calorimeters, respectively. The energy equivalent of the calorimeter is the amount of energy produced by the standard reaction and its accompanying side reactions divided by the corrected temperature rise. The observed temperature rise must be corrected for stirring energy and thermal leakage from the surroundings.

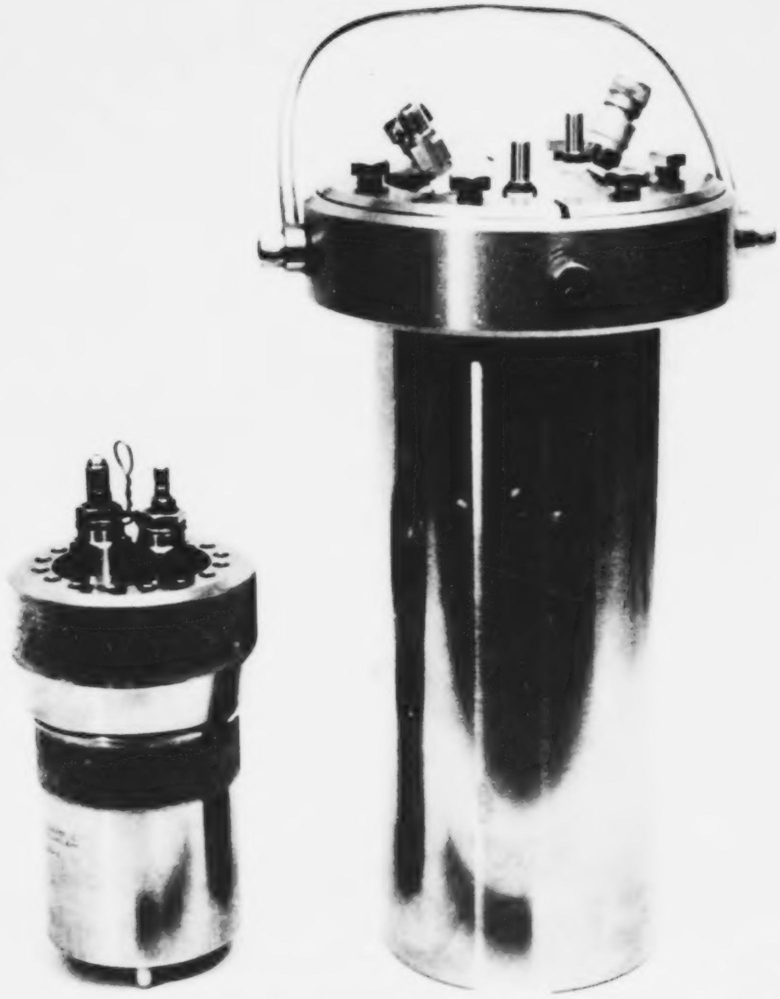
Multiplication of the energy equivalent (obtained from the calibration experiments) of the calorimeter by the corrected temperature rise (measured in the RDF combustion experiment) gives the total energy produced in the RDF combustion experiment. This total energy is then corrected for the various side reactions and divided by the mass of the RDF sample to produce the gross calorific value. In a typical RDF experiment, an equilibrated RDF pellet is weighed in a tared stainless steel crucible. The crucible and sample are supported inside an oxygen bomb. The sample is in contact with a 10 cm length of 0.127 mm (.005 in) diameter iron fuse wire. The bomb also contains 10 cm^3 of H_2O to dissolve the gaseous products of combustion and maintain an atmosphere that is saturated with water. The sealed bomb is then charged with 4.1 MPa (40.8 atm) of high-purity oxygen. The bomb is lowered into the calorimeter and the covered calorimeter is submerged in the constant temperature water bath. The calorimeter system is then heated to slightly below 25 °C. Temperature versus time data are collected to measure the temperature rise of the calorimeter as a result of the combustion of the RDF sample. Figure 6 is an



Inner Arrangement of Large Combustion Bomb

A Grounded Electrode	G Bomb Head	M Fuse Attachment Hook
B Valve	H Bomb Body	N Ring Holder
C Split Ring	I Handle	O Ring Support
D Compression Ring	J Gas Inlet Tube	P Sample Pellet
E Drop Band	K Ungrounded Electrode	Q Crucible
F Buna-N O-Ring	L Fuse	

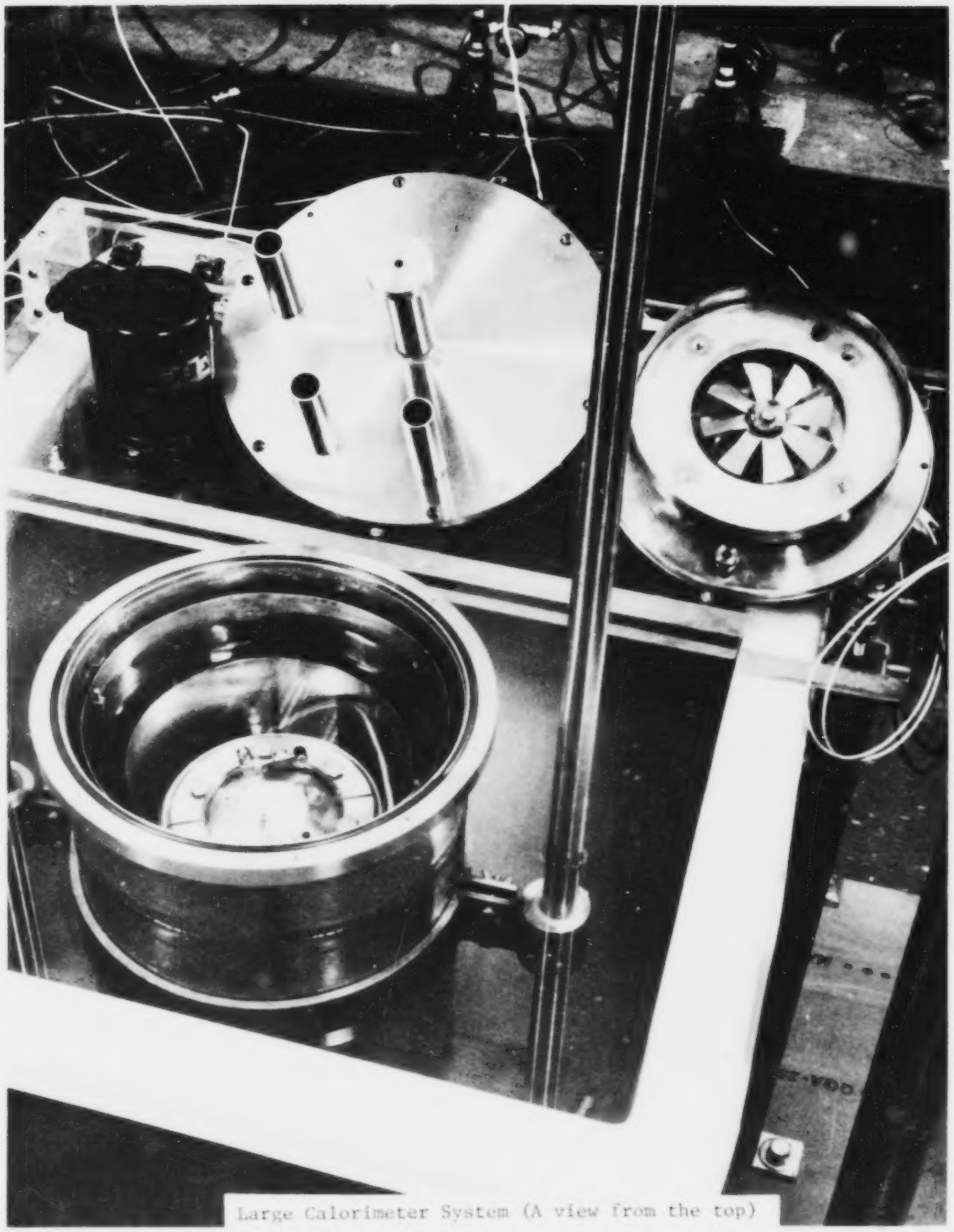
Figure 3



For Good Measure National Bureau of Standards

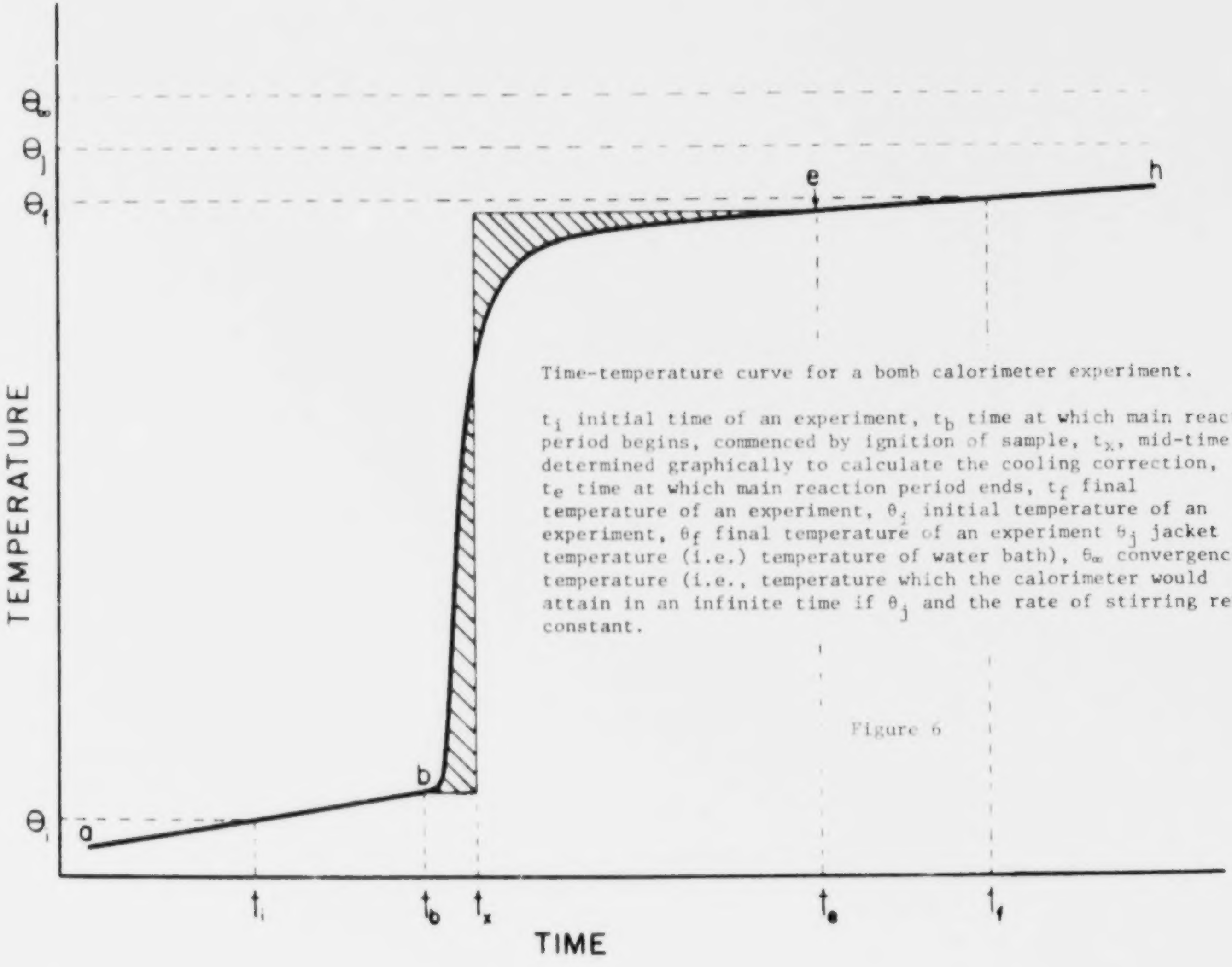
Small and large combustion bombs

Figure 4



Large Calorimeter System (A view from the top)

Figure 5



Time-temperature curve for a bomb calorimeter experiment.

t_i initial time of an experiment, t_b time at which main reaction period begins, commenced by ignition of sample, t_x, mid-time determined graphically to calculate the cooling correction, t_e time at which main reaction period ends, t_f final temperature of an experiment, θ_i initial temperature of an experiment, θ_f final temperature of an experiment θ_j jacket temperature (i.e.) temperature of water bath), θ_∞ convergence temperature (i.e., temperature which the calorimeter would attain in an infinite time if θ_j and the rate of stirring remain constant.

Figure 6

example of a time-temperature curve for a typical bomb calorimetric experiment. The temperature is measured during the period before the sample is ignited (line ab in Figure 6), during the reaction period immediately after the sample is ignited (line be in Figure 6), and during the period after the reaction is complete (line eh in Figure 6). The difference between the first point in the after-period and the last point in the fore-period gives the observed temperature rise. The slope of the fore- and after-periods allow one to calculate the portion of the temperature rise due to stirring energy and thermal leakage. The submerged calorimeter must be stirred at a constant rate to obtain a uniform and meaningful temperature vs. time curve. A preliminary experiment was performed to determine the amount of RDF sample necessary to produce about the same temperature rise in the calorimeters as that produced in our comparison reaction with benzoic acid, (a three and five degree (K) temperature rise in the small and large calorimeter, respectively).

DISCUSSION AND RESULTS

Calibration Experiments

It is necessary to determine the energy equivalent for both the large and conventional-sized calorimeter systems. The energy equivalent of a calorimeter is the total amount of energy that must be supplied to the calorimeter to produce a specified temperature rise in that calorimeter. The results of these calibration

Table I. Calibration Experiments of the Bomb Calorimeters

	Small Calorimeter					Large Calorimeter		
Expt. No.	1046	1047	1048	1049	1050	2006	2010	2011
$\Delta U_c{}^\circ, T_h$(J·g^{-1})	26410.68	26410.68	26410.68	26410.68	26410.68	26411.36	26411.36	26411.36
m_{BA}(g)	1.635791	1.632017	1.650145	1.639178	1.640040	14.998983	16.272774	16.289839
q-BA(J)	43202.35	43102.68	43581.45	43291.81	43314.57	396143.48	429785.98	430236.69
q-ign(J)	1.08	1.72	0.94	1.19	1.01	2.19	1.59	1.92
q-Fe(J)	----	----	----	----	----	56.05	38.80	38.82
q-HNO_3(J)	6.80	5.90	5.77	5.20	5.30	183.43	57.87	57.87
q-wc(J)	37.13	34.59	34.96	34.85	34.80	383.16	510.15	510.78
q-$T_f$corr(J)	.02	.04	-.02	.03	.02	5.84	-.98	- 1.25
q-C_{corr}(J)	----	----	----	----	----	-101.60	-29.50	-19.66
Q-Total(J)	43247.38	43144.93	43623.10	43333.08	43355.70	396672.54	430363.91	430825.16
ΔT-corr(deg)	2.969681	2.963055	2.995277	2.976097	2.977749	4.601897	4.992241	4.997143
E-cal(J·deg^{-1})	14562.97	14560.96	14563.96	14560.37	14559.89	86197.61	86206.56	86214.30
C_v-cont.(J·deg^{-1})	6.87	6.87	6.89	6.88	6.88	31.78	49.88	49.89
E-si(J·deg^{-1})	14556.10	14554.09	14557.07	14553.49	14553.01	86165.83	86156.68	86164.41
E-si mean (J·deg^{-1})			14554.75				86162.31	
Std. Dev. (J·deg^{-1})			1.72(0.012%)				5.00(0.0058%)	
Std. Dev. Mean (J·deg^{-1})			0.78(0.0053%)				2.89(0.0034%)	

experiments are presented in Table I. Experiment numbers 1046 through 1050 were performed in the small conventional calorimeter and 2006, 2010 and 2011 were performed in the large calorimeter. In a calibration experiment, one accounts for all energy supplied to the calorimeter system and measures the resulting temperature rise. The line identifications in column 1 of Table I contain the different sources of energy in a typical calorimetric experiment. A comparison of the small and large calorimeter entries will point out some of the differences between the two calorimeters. $\Delta U_c^\circ, T_h$ is the energy of combustion of benzoic acid at the specified reference temperature, T_h. The small calorimeter is referenced to 28 °C and the large calorimeter is referenced to 30 °C. The heat of combustion of the calorimetric standard, benzoic acid, is known to one part in ten thousand. From the mass of benzoic acid, shown in line 3, the energy supplied by combustion of benzoic acid can be calculated and is presented in line 4, q-BA. Line 5 shows the electrical energy that was supplied to ignite the sample. The platinum fuse wire of the small calorimeter is heated electrically to its melting point to ignite the samples. The molten platinum fuse solidifies and therefore supplies no energy to the small calorimeter. In the large calorimeter a iron fuse wire was used. The electrical energy necessary to melt the iron fuse wire must be accounted for, but in addition, the molten iron burns in oxygen producing iron oxides. The quantity of iron fuse wire burned and the energy of combustion of the iron fuse wire are used to calculate the energy supplied by the combustion of iron, q-Fe. Some of the nitrogen impurities in the oxygen are converted to nitrogen oxides which react with water to form nitric acid. The quantity of nitric acid produced is measured and from its energy of formation, q-HNO_3 is calculated. In high-precision combustion calorimetry, it has become standard practice to apply corrections proposed by Washburn [7] that produce calorimetric data referenced to a standard set of conditions. These corrections to standard states for the isothermal bomb process at 25 °C and unit fugacity are known as Washburn Corrections and are presented as q-wc. The small calorimeter is designed to operate between 25 °C and 28 °C while the large calorimeter operates between 25 °C and 30 °C. In actual practice, the final temperature of our experimental reaction is not exactly 25 °C or 30 °C and therefore, a small correction must be applied to the calorimetric data for high precision work and is shown as q-T_f corr. in Table I. Due to the limited quantity of oxygen in the large bomb, a few tenths of a milligram of carbon residue were found in the combustion crucible. The stated energy of combustion of benzoic acid assumes complete combustion and therefore a small correction for unburned carbon was applied to the results. The algebraic sum of energy from various sources yields, the total energy supplied to the calorimeter, Q-Total.

Some additional discussion is warranted in regards to the unburned carbon residue. Stoichiometrically, 2 grams of oxygen are required for the combustion of 1 gram of benzoic acid. Normally, 10 grams of oxygen are used for each gram of benzoic acid to insure complete combustion in the conventional-sized bomb. Calorimetrically, it has been found in practice that 6.5 g of O_2 per gram of benzoic acid is the minimum requirement for complete combustion in a bomb calorimeter. The large bomb utilizing a 16.5 gram benzoic acid sample and 4.1 MPa (40 atm) of oxygen contains about 100 grams of O_2. This is on the borderline of the minimum amount of oxygen necessary for complete combustion in bomb calorimetry. However, in our experiments the total correction for unburned carbon is usually less than 40 joules for a 400 000 joule experiment (1 part/10 000) and if completely neglected would be acceptable for precision calorimetry of benzoic acid. The correction for unburned carbon is given in Table 1 for the large calorimeter data and presented as q-C_{corr}.

The corrected temperature rise of the calorimeter, ΔT-corr, is measured and with the total energy supplied to the calorimeter, the energy equivalent, E_{cal}, of the calorimeter is determined. The mass of water introduced into the bomb, the crucible and the sample may change from experiment to experiment, and when accounted for in the energy equivalent of the calorimeter, the energy equivalent of the "empty" calorimeter, E_{si}, is obtained.

The important parameters to compare between the two calorimeters are the energy equivalents and the total energy capacities of the two calorimeters. The energy equivalent of the small calorimeter is 14 555 joules per degree while that of the large calorimeter is 86 162 joules per degree. This is about six times that of the small calorimeter. The large calorimeter has a total energy capacity of 430 810 joules compared to 43 665 joules of the small calorimeter. Therefore, a sample ten times larger and thus requiring less particle size reduction can be used in the large calorimeter. This is extremely important since the calorific value of a solid fuel can now be determined with only minimal processing and the suspected chemical changes which are imposed upon the refuse or RDF analysis sample as a result of size reduction, can now be determined quantitatively.

RDF Combustion Experiment

In a calorimetric experiment, the calculations are done in reverse order in comparison to a calibration experiment. The temperature rise of the calorimeter is measured and with the mean energy equivalent of the empty calorimeter plus its contents, the total energy supplied to the calorimeter is calculated. In addition to the corrections applied to the benzoic acid experiments, a correction is applied for the formation of sulfuric acid because of a small amount of sulfur (~0.1 percent) contained in the d-RDF sample. Since the actual reactants and products in the RDF experiments are unknown, the Washburn corrections (used in high-precision calorimetry) are not applied. In addition,

Table II. MAF Calorific Values in MJ·kg^{-1} (Btu·lb^{-1}) of Teledyne National RDF

	Small Calorimeter		Large Calorimeter	
	Expt. No.	Q_v	Expt. No.	Q_v
	1052	24.95 (10726)	2030	25.27 (10866)
	1053	24.51 (10539)	2032	26.09 (11216)
	1054	25.01 (10752)	2033	24.96 (10732)
	1056	24.78 (10656)	2034	24.42 (10501)
	1057	25.06 (10776)	2038	24.77 (10650)
	1058	25.06 (10776)	2039	24.39 (10485)
	1059	25.20 (10835)		
	1060	25.12 (10799)		
	1061	25.09 (10788)		
	1062	25.08 (10781)		
Range	(10539-10835)		(10485-11216)	
Mean	(10743)		(10742)	
Std. Dev.	(86)		(273)	
%Std. Dev.	0.80%		2.54%	

complete combustion is assumed in the RDF experiments. Subtraction of the energy from all sources except the sample burned yields the energy supplied by combustion of the sample alone. Using the mass of sample burned, the calorific value of the solid fuel is calculated.

Table II presents the calorific values obtained on an RDF sample from Teledyne National. The values presented from the small calorimeter were obtained on small samples which required considerable processing as outlined in the experimental section earlier. The values determined on d-RDF samples in the large calorimeter were obtained on extrusions with no further processing.

Table II presents moisture- and ash-free calorific values obtained from these two types of calorimetric samples. Typical RDF samples have a moisture- and ash-free calorific value of between 9 000 and 10 000 Btu$(lb)^{-1}$. The Teledyne National samples studied are obviously atypical and exhibit an unusually high heating value.

Ten experiments in the small calorimeter on "homogeneous" RDF yielded a mean calorific value of 10 743 Btu$(lb)^{-1}$ and a percent standard deviation of 0.80 percent while six experiments on as received RDF samples with no further processing yielded a mean value of 10 742 Btu$(lb)^{-1}$ and a percent standard deviation of 2.54 percent in the large calorimeter. This is a significant finding when one considers the large difference in physical appearance of the two types of samples.

The range of calorific values is much larger on the large unprocessed samples than on the small processed ones. Calorific values were dispersed over the range from 10 539 to 10 835 Btu$(lb)^{-1}$ for the small calorimeter samples while a range of 10 485 to 11 216 Btu$(lb)^{-1}$ was observed for the large calorimeter samples. These results suggest that the unprocessed samples are more heterogeneous and that the calorific values would scatter widely. However, if a sufficient number of experiments were performed, the mean values would still be the same (or very nearly so) for the two types of sample populations. A closer look at the heating values obtained in the large calorimeter reveals that five of the six values are close together and that one value, 11 216 Btu$(lb)^{-1}$, lies further from the mean. However, the 11 216 Btu$(lb)^{-1}$ value lies only 1.7 standard deviations from the mean, and thus should be included as part of the same sample population.

If the high calorific value were to be omitted, the mean calorific value would be 10 647 Btu$(lb)^{-1}$ which is less than one percent from the mean obtained when 11 216 Btu$(lb)^{-1}$ is included. This omission would change the percent standard deviation from 2.54 percent to 1.51 percent.

Several things could account for the spread of calorific values from the large calorimeter. In addition to the sampling problems associated with RDF, the moisture and ash contents are very important parameters. Table III contains the moisture and ash contents used to calculate the moisture- and ash-free results from the as-determined calorimetric data which are presented in Table II. From the percent moisture of samples 1052, 1053 and 1054, we attribute the fluctuations in the moisture content to the relative humidity changes of the room. Therefore, sample 1056 through 1062 were equilibrated in a constant humidity atmosphere and all had virtually the same moisture content. Water was absorbed or evaporated from the samples during the weighing process but always at a rate which was not readily reflected in the corresponding calorific value. This was accomplished by maintaining the constant humidity container at the average relative humidity of the room (~45 percent). One reason for the good precision of the small calorimeter results is that the moisture was virtually constant for all samples and was determined on the calorimetric sample directly. This was not true for the large calorimeter samples. With the small samples, 48 hours were sufficient for equilibration, but the as-received extruded pellets for the large calorimeter had approximately 13 percent moisture and equilibrated very slowly in our constant humidity atmosphere. Since equilibrated samples have the same moisture content, we feel that separate moisture experiments would give an average moisture value indicative of all the equilibrated RDF samples. Two experiments were carried out on several extruded pellet fragments each weighed about 5 grams, and yielded moisture values of 5.71 and 5.92 percent. Two experiments were performed on extruded pellets of approximately the same size (∿25 grams) as the combustion samples and yielded moisture contents of 6.82 and 6.30 percent. We feel that none of the extruded pellets had equilibrated completely and that the equilibration was very slow and largely dependent upon the size of extruded pellets chosen for equilibration. The moisture determinations were done on different days during the period that the calorimetric experiments were being performed. We feel that the moisture determinations of the extruded pellets of approximately the same size (∿25 grams) were more representative of our calorimetric samples. We, therefore, used an average moisture of 6.56 percent to calculate calorific values on a moisture-free basis. The large uncertainty of the actual moisture of each calorimetric sample may be the cause for the large range of heating values calculated for measurements carried out in the large calorimeter.

Our earlier experiences in determining MAF heating values of RDF indicated that, even with the highly processed and blended RDF, the ash content varied from sample to sample. We therefore adopted a procedure in our laboratories of determining the ash from the amount of residue remaining in the bomb after a combustion experiment. This has allowed us to calculate the actual "ash" for each calorimetric samples. For the small calorimeter samples, the actual moisture and ash contained in each sample is known and allows us to calculate the MAF calorific value with a percent standard deviation of less than one percent. The ash measurements were determined on each of the large calorimeter samples but an average of moisture content values was used to calculate the MAF calorific values with a percent standard deviation of approximately 2.5 percent.

CONCLUSION

We have designed and constructed a bomb calorimeter which is capable of handling a sample ten times heavier than our conventional-sized bomb calorimeter. Suspected differences in the character of refuse or RDF samples because of inappropriate sampling or intensive size reduction can be determined from calorimetric measurements in this large calorimeter. This isoperibol (isothermal-jacket) calorimeter is an enlarged and modified version of our conventional-sized calorimeter with the same basic principles of operation. The large calorimeter has been calibrated to better than one part in ten thousand and can be considered a precision calorimeter like our conventional-sized one. However, the internal volume (1.85 liters) of the bomb can contain only the minimum amount of oxygen usually required for complete combustion of solid samples (4.1 MPa of oxygen for a 25 gram RDF sample). This large bomb calorimeter has been calibrated to better than 1 part/10 000

Table III. Residual Moisture and Ash Data

Sample Calorimeter Samples			Large Calorimeter Samples		
Expt. No.	% Moisture	% Ash	Expt. No.	% Moisture	% Ash
1052	3.74	11.57	1	5.71	-----
1053	4.15	11.50	2	5.92	-----
1054	3.75	13.94	3	6.82	-----
1056	3.89	11.94	4	6.30	-----
1057	3.82	11.87	2030	----	15.01
1058	3.85	12.25	2032	----	13.37
1059	3.88	11.84	2033	-----	14.90
1060	3.96	12.08	2034	-----	14.46
1061	3.93	11.76	2038	-----	13.32
1062	3.88	12.04	2039	-----	14.18

and perhaps is the most precise large bomb calorimeter being used in this country today.

One objective of this research project is to decide whether or not the calorific value of refuse is altered by the amount of particle size reduction. For a limited number of experiments in both the large and small calorimeters, we found that the calorific value of a given laboratory sample of Teledyne National RDF was unaffected by particle size reduction. As-received extruded RDF pellets were found to have the same mean calorific value as pellets prepared from 2 mm (10 mesh) particles which were obtained by the milling of as-received extruded RDF pellets followed by several riffling and blending operations.

The precision (standard deviation) obtained from pellets prepared from 2 mm particles was three times better than that obtained with pellets where no processing was done in our laboratory. The reason for this lower precision is not known but we suspect that it is the result of a greater degree of heterogeneity in the unprocessed sample and the imprecision in our moisture determinations. We believe that more precise moisture data can be obtained if as-received extruded RDF pellets are equilibrated at a constant humidity atmosphere and for each calorimetric sample, a moisture sample also is selected. If the calorimetric and moisture sample have the same history and are weighed concurrently, then the moisture contents should be comparable. In addition, it is worth noting that moisture determinations on pellets prepared from 2 mm (10 mesh) particle were found to yield constant values after they were air-dried and equilibrated at constant humidity. However, particle size reduction does alter the moisture content and careful accounting of the moisture is necessary.

We found that the determination of the ash content by conventional dry ashing techniques yields a range of values for "homogeneous," milled and blended 2 mm (10 mesh) particles of RDF. We suggest that the non-combustible fraction of RDF clings to the fibrous RDF particles and is not evenly distributed by the blending process. Therefore, we adopted a procedure of determining the ash from the combustion residue remaining in the bomb.

In summary, it appears the calorific value of the Teledyne National RDF is unaffected by the particle size reduction procedures carried out in our laboratory. Also, to obtain good precision, one must apply the ash residue remaining in the combustion after an experiment to the calculation of a given calorific value. To avoid any sample processing for the large calorimeter experiments, a "twin" moisture determination pellet must be selected and run concurrently with the calorimetric sample. One can draw the general inference from the calorimetric results that processing of a sample, which has been extruded from minus 1.9 cm (0.75 inch) pieces of RDF, down to a particle size below 0.2 cm (0.08 inch) can be attained without changes in chemical composition or representativeness.

REFERENCES

[1] Kirklin, D. R., Mitchell, D. J., Cohen, J., Domalski, E. S., and Abramowitz, S., NBSIR 78-1494, December 1978.

[2] Coops, J., van Nese, K., Kentee, A., and Dienske, J. W., Rec. Trav. Chim. 66, 113-130 (1947).

[3] Coops, J., and van Nes, K., Rec. Trav. Chim. 66, 131-141 (1947).

[4] Gundry, H. A., Harrop, D., Head, A. J., and Lewis, G. B., J. Chem. Thermodynam. 1, 321-332 (1969).

[5] Prosen, E. J., Experimental Thermochemistry, Chapter 6, F. D. Rossini, Editor, Interscience Publishers, New York, 1956.

[6] Jessup, R. S., NBS Monograph 7, 1960, "Precise Measurement of Heat of Combustion with a Bomb Calorimetery," (U.S. Government Printing Office, Washington, DC 20420).

[7] Washburn, E. W., J. Research NBS 10, 525 (1933), RP546.

TECHNICAL, ECONOMIC AND MARKET EVALUATIONS ON THE USE OF WASTE GLASS IN STRUCTURAL CLAY BRICK MANUFACTURE

Ashok K. Gupta*
Resource Recovery Systems
Raytheon Service Company
Burlington, Massachusetts

Laura A. Arozarena
Solid & Hazardous Waste Research Division
U.S. Environmental Protection Agency
Cincinnati, Ohio

ABSTRACT

This paper gives the results of an investigation conducted on the use of refuse-derived waste glass in structural clay brick manufacture. Waste glass was produced at Occidental Research Corporation's La Verne, California prototype resource recovery plant. Laboratory testing was performed at the U.S. Bureau of Mines, Tuscaloosa, Alabama; and commercial testing was performed at Glen-Gery Corporation's 120,000 bricks per day plant in Reading, Pennsylvania. For commercial testing, standard size (2 1/4 inch x 3 5/8 inch x 8 inch) solid bricks, with and without glass, were formed by stiff-mud extrusion. These were fired in a commercial tunnel kiln at a 100°F lower temperature than normally required for firing regular bricks. Bricks containing glass were of comparable quality to regular bricks fired at normal temperature. However, these glass-containing bricks were of a much higher quality (absorption 35 percent lower and compressive strength 50 percent higher) than the regular bricks fired at the same temperature. The optimum waste glass-to-clay ratio was determined to be 15:85. At this ratio, the following specifications for waste glass were established: particle size $\leq$100 mesh; organic content $\leq$8 weight percent; glass content $\geq$60 weight percent; water soluble salt content $\leq$0.46 weight percent; and water soluble sulfates $\leq$0.035 weight percent.

The reduction of firing temperature of the tunnel kiln by 100°F can possibly increase brick production by 22 percent. Assuming a 15 percent increase in production and energy savings,

---

*Formerly employed by Occidental Research Corporation, Irvine, California and considering the cost of handling glass at resource recovery and brick plants, the value of waste glass was calculated to be $28.10 per ton. It is our opinion that waste glass slimes can be used in brick manufacture with little or no further processing. A conceptual process flowscheme was developed to process the entire waste glass stream for use in brick manufacture. The net cost to process this stream from 200 TPD of glass-rich residue was calculated to be $13.06 per ton of glass product.

Marketing survey results show a concentration of brick plants generally in the areas of existing or potential locations of resource recovery plants and a good potential for the consumption of approximately half of the waste glass by the brick industry.

INTRODUCTION

The U.S. Bureau of Mines (USBM) has established, by laboratory tests, that the finely-ground glass mixture from incinerator residue is both suitable and beneficial in manufacturing structural clay bricks (1). This laboratory work has been confirmed by others (2,3), and the potential value of such a product to brick manufacturers seems widely accepted. The laboratory tests established that the use of waste-glass mixtures in structural clay bricks improves such important properties as moisture absorption and compressive strength. The reported laboratory tests established that test bars can be fired at lower firing temperatures without sacrificing quality. This results in an increased brick production rate.

There have been no commercial-scale tests on glass-rich mixtures derived from incinerator residue and, more importantly, no major tests prior to this work on glass-rich mixtures derived from rat refuse processing. Of the 15 million tons of glass discarded in municipal waste annually, only 2 million tons pass through incinerators (1), and this tonnage is declining.

The main thrust of this program was to demonstrate, by commercial-scale tunnel kiln testing, that waste glass slimes derived from raw refuse processing act as flux in making bricks and that the glass reduces the final firing temperature required in the manufacture of bricks. Reduction of firing temperature signifies increased production from kilns with subsequent reductions in production and energy costs.

In examining the feasibility of using raw refuse-derived glass-rich mixtures in structural clay brick manufacture, both laboratory- and commercial-scale testing were employed. The effect of waste glass addition to clay bricks was evaluated using three select clays. This investigation included two types of waste glass mixtures which are current or potential waste products of most resource recovery plants: glass cullet feedstock and glass slimes.

The primary mixture studied, known as "slimes", is a waste product of resource recovery plants using the froth flotation process for cullet quality glass. Currently, of six commercial resource recovery plants committed for cullet quality glass recovery, four plants will be using the froth flotation process (4). About (10-15%) of the entire waste glass stream of a resource recovery plant reports as slimes.

The second type of waste glass mixture is the glass-rich residue produced by most resource recovery plants which separate combustibles, inorganics and metals thorugh shredding, magnetic separation, classifying and screening operations. This glass-rich mixture is the feedstock for the cullet quality glass recovery process and contains most of the glass found in raw refuse. Because of economical and/or marketing limitations, cullet quality glass recovery from this mixture is not feasible at some resource recovery plants.

One of the major findings of this study was that waste glass is valuable to the brick producer. Due to the lack of any long-term commercial testing, one brick producer designated a value of $4-6 per ton FOB brick plant for waste glass, which approximates the replacement cost of their raw materials (clays). The cost of raw materials varies from $2 to $5 per ton in the brick industry. During this investigation, it was concluded that a greater than $4-6 per ton value could be assigned to waste glass due to decreased brick production cost and energy savings by addition of waste glass to the brick mix.

A conceptual process flowsheet, mass balance and economics for dry beneficiation of 200 tons per day of waste-glass residue were developed for brick use and are summarized below.

Results of the marketing survey are presented. Lists of existing brick plants and existing or potential resource recovery plants were prepared. Locations of brick plants within a 50-100 mile radius of resource recovery plants were identified. More than 25% of the brick companies were contacted by the Occidental Research Corporation for the market survey.

TECHNICAL EVALUATION

The technical evaluation consisted of exploratory, laboratory, and commercial testing at: U.S. Bureau of Mines, Tuscaloosa, Alabama; Glen-Gery Corporation, Shoemakersville, Pennsylvania; and Glen-Grey Corporation, Reading, Pennsylvania.

Materials and Methods

Three types of clays were included in this evaluation, ranging in composition from 100% shale body to 100% clay body.

Glen-Gery Brick Mix --

The Glen-Gery brick-mix is a red burning shale generally known as Red Shale, which consists of 100% shale body. It is mined from the Reading, Pennsylvania area. This shale clay is fired to 7-9% absorption at 1920°-1950°F, and was included in the study because it is representative of the brick mix used to produce approximately half of the structural clay bricks produced in the United States.

Michael-Kane Brick Mix --

This brick mix is 100% clay, and is generally called Connecticut Red Clay. It is mined from the Middletown, Connecticut area from a rather recent clay deposit. It is fired fired to 12% absorption at 1800°F with 72-hour soaking at 1800°F in a scove kiln. This mix was included in the study because it is 100% clay and the brick plant is located within 43 miles of the CEA/ORC resource recovery plant under construction at Bridgeport.

San Valle Tile Mix --

This mixture of red firing clays (60%) and shale (40%), referred to as San Valle Tile mix, consists of red and grey clays and brown shale. The clays and shale are mined separately from the neighboring areas of Corona, California (from 20 to 90 miles) and mixed at the plant site in proportions of 40% red clay, 40% brown shale and 20% grey clay. The tile mix is fired to 9-10% absorption at 1860°F with a 10-hour soaking at 1860°F in a tunnel kiln. This mix was included for the potential application of research results to the sewer pipe and roof-tile industry, whose products command higher unit prices than bricks.

Exploratory Testing

These tests were conducted to examine the feasibility of utilizing waste glass in making structural clay bricks, to characterize the raw materials, and to establish specifications for waste glass that can be effectively used in brick manufacture with minimal waste glass processing.

The two types of waste glass used for tests are described in the following paragraphs.

Waste Glass Mixture I (WGM-I)--

WGM-I is a fine-sized glass-rich mixture, generally known as glass slimes, which is a waste product of resource recovery plants using the froth flotation process for recovering cullet quality glass. This mixture was reclaimed at Occidental Research Corporation's (ORC) glass prototype plant at La Verne, California. A schematic flowsheet of this plant is shown in Figure 1. The processing steps include trommeling the glass-rich material (derived by shredding and air classifying raw municipal solid waste at 1/2 inch screen, and processing the -1/2 inch fraction through an organic removal circuit (jig or screw classifier), grinding circuit and classification circuit. In the classification circuit, finer than 150 mesh

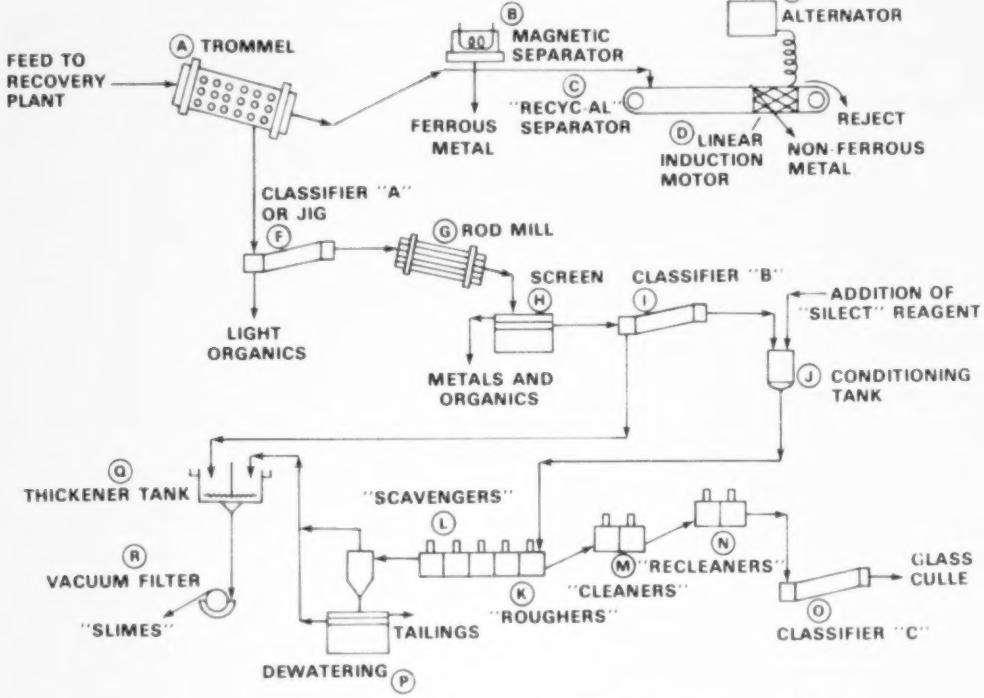

FEED TO RECOVERY PLANT
Ⓐ TROMMEL
Ⓑ MAGNETIC SEPARATOR
FERROUS METAL
Ⓒ "RECYC-AL" SEPARATOR
Ⓓ LINEAR INDUCTION MOTOR
Ⓔ ALTERNATOR
REJECT
NON-FERROUS METAL
CLASSIFIER "A" OR JIG
Ⓕ
LIGHT ORGANICS
Ⓖ ROD MILL
SCREEN Ⓗ
METALS AND ORGANICS
CLASSIFIER "B" Ⓘ
ADDITION OF "SILECT" REAGENT
Ⓙ CONDITIONING TANK
Ⓠ THICKENER TANK
Ⓡ VACUUM FILTER
"SLIMES"
"SCAVENGERS" Ⓛ
Ⓚ "ROUGHERS"
"CLEANERS"
Ⓜ "RECLEANERS" Ⓝ
TAILINGS
DEWATERING Ⓟ
Ⓞ CLASSIFIER "C"
GLASS CULLE

Figure 1. Flowsheet of ORC's La Verne Prototype Plant

particles are removed from the feed to flotation circuit by the combination of a cyclone and screw classifier. Coarse but lighter particles, such as organics which were not removed in the organic removal circuit, are also removed with finer particles. This stream is processed through a thickener and a rotary vacuum drum filter, producing a cake containing 25% moisture. This material is then air dried. The balance of the material in the plant is processed through the flotation circuit which produces high purity glass cullet used in manufacturing glass containers.

WGM-I was produced from glass-rich material obtained from the Los Gatos, California and Ames, Iowa resource recovery plants. In the Los Gatos, resource recovery plant, raw municipal solid waste (MSW) is processed through a hammermill and an air classifier. The air classifier heavies were purchased from the Los Gatos plant and were trucked to the La Verne plant site where they were stored in roll-off bins, reclaimed and fed manually to the trommel infeed conveyor. In the Ames resource recovery plant, MSW is processed through two stages of shredding and air classification. The Ames plant air classifier heavies contained a large amount of organics and were processed through additional screening and air classification before processing through the La Verne glass plant.

Table 1 shows the particle size distribution and organic content (as determined by the loss on ignition at 500°C) of WGM-I produced from the glass plant feed from Los Gatos, California and Ames, Iowa. A screw classifier was used in the organic removal circuit to produce this mixture. The higher organic content of WGM-I produced from Ames, Iowa feed is probably due to two-stage shredding prior to air classification at the Ames plant.

Waste Glass Mixture II (WGM) --

WGM-II is a glass-rich residue derived at most resource recovery plants by shredding, air classifying and screening the heavy fraction from the air classifier. The "through" fraction of the screen is ground to 80% passing -200 mesh, a particle size considered most effective in making structural clay bricks (1). In areas where resource recovery plants are not large enough to support cullet quality glass recovery or cullet market outlets are too distant or limited, presently this glass-rich material is landfilled, unless an alternative use is found. The recovery of this material was selected as an alternative to landfilling.

TABLE 1. PARTICLE SIZE DISTRIBUTION AND ORGANIC CONTENT OF WGM-I

	Ames, Iowa			Los Gatos, California		
Particle Size	% Retained	Cumulative % Retained	% LOI*	% Retained	Cumulative % Retained	% LOI*
+100	23.1	23.1	31.2	21.2	21.2	25.0
-100+200	26.0	49.1	5.9	51.5	30.3	4.5
-200+325	17.9	67.0	5.5	68.2	16.7	5.5
-325	33.0	100.0	7.2	100.0	31.8	6.5
Total LOI			12.2			9.7

*LOI = Loss on ignition

The sample was prepared from glass-rich material obtained from the Ames, Iowa resource recovery plant. Approximately 600 lb. of this material was grounded by SELREX Corporation, Chatsworth, California, in a 5 ft diameter by 6 ft long batch ball mill for about 16 hours. The ground material was screened at 100 mesh. The +100 mesh material was discarded (9% of total) and 200 lb. of -100 mesh material was sent to the USBM for exploratory testing. Particle size distribution and organic content (as determined by loss of ignition at 700°C) are given in Table 2. Chemical and physical properties of WGM-I and WGM-II are listed in Table 3.

Clays --

To keep the number of tests within manageable limits, only the Glen-Gery brick mix was used for exploratory testing. This shale is a mixture of quartz, illite, chlorite and a small amount of geothite.

Chemical analyses and pyrometric cone equivalent (PCE) of Glen-Gery brick mix are listed in Table 4.

Fluxing Tests --

Preliminary fluxing tests were made to examine the feasibility of utilizing these waste-glass mixtures in brick manufacture. A mixture of 10% WGM-I and II and 90% Glen-Gery brick mix was used. This ratio was based on a USBM investigation (1). Results plotted in Figure 2 show that for a given finite quantity of available waste glass, the largest energy savings to a brick manufacturer occurs when bricks are made with 10% waste glass rather than with higher glass compositions. Fluxing test results determined that waste glass can be used as flux and established -100 mesh as optimum particle size and $\leq 8\%$ as maximum tolerable organic content.

Twenty 1 inch x 1 inch x 7 inch bars were formed at the USBM for each composition by using a laboratory de-airing extrusion machine. The bars were dried for 24 hours in air followed by 24 hours at 212°F. They were then fired to 1800° and 1850°F at a rise of 100°F per hour in an electrically-heated kiln.

TABLE 2. PARTICLE SIZE DISTRIBUTION AND ORGANIC CONTENT OF WGM-II

Particle Size	% Retained	Cumulative % Retained
+200 mesh	8.8	8.8
-200+325 mesh	19.6	28.4
-325 mesh	71.6	100.0

Loss on ignition - 11.1%

TABLE 3. CHEMICAL AND PHYSICAL PROPERTIES OF WGM-I AND WGM-II

Chemical/Physical Properties	Weight % WGM-I	 WGM-II
SiO_2	54.6	54.3
Al_2O_3	7.1	3.8
Fe_2O_3	2.3	2.0
K_2O	1.6	0.7
Na_2O	6.8	7.9
MgO	1.5	3.4
CaO	8.0	12.7
pH	8.6	10.5
*PCE (Cone)	03-01	01
(temp., °F)	2068-2152	2152

*PCE = Pyrometric cone equivalent

TABLE 4. CHEMICAL ANALYSES AND PCE OF GLEN-GERY BRICK MIX

Oxide	Weight %
SiO_2	55.8
Al_2O_3	22.7
Fe_2O_3	8.4
K_2O	3.6
Na_2O	0.7
MgO	1.1
CaO	0.2
TiO_2	1.0

Loss on Ignition at 1000°C - 6.0%

PCE - 13

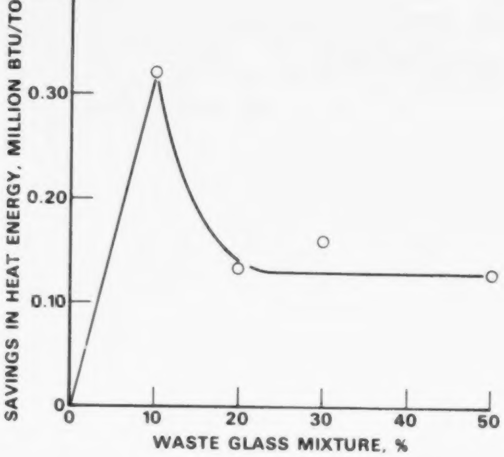


Figure 2. Savings in Heat Energy by Increments of 10% Substitution of Waste Glass Mixtures for Clay

Results in Table 5 show that 10% WGM-I and WGM-II added at a firing temperature of 1800°F behaves as a flux and reduces the absorption by 11.4% and 16.9% respectively and increases the compressive strength by 17.4% and 20.3% respectively.

Waste Glass Particle Size --

Exploratory fluxing tests were made to determine the optimum particle size for the WGM-I fraction. A mixture of 10% waste glass and 90% Glen-Gery brick mix was used for these tests. Results are given in Table 6 which indicates that -100 mesh waste glass is almost as effective a flux as -200 mesh waste glass; thus the -100 size was used throughout the remainder of the study.

Organic Content --

Exploratory tests were made at Glen-Gery Corporation to examine the following two concerns: fluxing effect of waste glass contaminated with various levels of organics; and the maximum organic content that can be tolerated in brick manufacture without causing black coring in the bricks. Black coring is caused by the reaction of unburnt residual carbonaceous matter with ferrous iron (Fe^{++}). This undesirable condition could cause strength variations in the product, rusty iron stain, efflorescence and bloating problems. Results showed no appreciable change in fluxing effect by varying the level of organics although black coring was caused in

TABLE 5. FLUXING FIRING RESULTS ON 10% ADDITION OF WASTE GLASS MIXTURES I AND II WITH GLEN-GERY BRICK MIX

Waste Glass Additions	% Shrinkage 1800°	% Shrinkage 1850°	% 5-Hr Absorption 1800°	% 5-Hr Absorption 1850°	Compressive Strength,psi 1800°	Compressive Strength,psi 1850°
No addition	2.8	4.8	16.6	11.7	3450	6500
WGM-I	2.5	4.5	14.7	10.7	4050	7150
WGM-II	3.0	4.7	13.8	10.6	4150	5950

TABLE 6. FLUXING RESULTS ON 10:90 GLASS-CLAY MIXTURE WITH VARIOUS PARTICLE SIZE GLASS

Waste Glass Additions	% Shrinkage 1800°	% Shrinkage 1850°	% 5-Hr Absorption 1800°	% 5-Hr Absorption 1850°	Compressive Strength,psi 1800°	Compressive Strength,psi 1850°
-100 mesh	2.8	4.5	14.5	10.1	3300	5750
-150 mesh	3.8	4.8	13.8	9.5	4150	6700
-200 mesh	2.8	4.7	14.0	9.5	4150	5800

bricks containing waste glass with more than 8% organics.

Waste glass samples containing 0% to 12% organics were made by burning the waste glass at 700°C and then blending the burnt waste glass with unburnt waste glass to desired proportions. Fluxing tests were made on 1 inch x 1 inch x 7 inch bars of 90:10 clay mixtures. Fluxing results are given in Table 7.

These test bars did not show any black coring. It was felt that this effect may be due to the smaller cross sectional area of the test bars permitting complete carbon burnout. Therefore, black coring tests were conducted on standard-size, hand-molded bricks with 90:10 clay-glass mixture. Waste glass mixtures used in this test contained 0%, 5%, 8%, 10%, and 15% organics by weight as determined by loss on ignition at 700°C. These hand-molded bricks were fired in the tunnel kiln during regular production at Glen-Gery Corporation's Reading, Pennsylvania plant. These fired bricks were cut in half by a diamond saw to examine the inside of the brick for black coring. Bricks containing waste glass with 0%, 5%, and 8% organics did not show any black coring, whereas the bricks containing waste glass with 10% and 15% organics did show black coring.

Based on the above results, the following specifications were established for waste glass to be used for laboratory and semi-commercial testing:

1. Particle size - minus 100 mesh

TABLE 7. FLUXING TESTS OF 90:10 CLAY-GLASS MIXTURE, WITH VARIOUS GLASS ORGANIC CONTENT

% Organic Content of Waste Glass	Water Absorption 24 Hr Cold 1850°F	1950°F	5-Hr Boil 1850°F	1950°F	Sat. Coef. 1850°F	1950°F	Modulus of Rupture psi 1850°	1950°
0	3.1	1.2	6.3	3.0	0.49	0.39	3798	3933
2	3.5	1.5	6.8	3.8	0.51	0.41	3357	4347
5	4.0	1.4	7.1	3.6	0.56	0.39	3347	4275
7	4.8	1.8	8.6	4.6	0.56	0.39	3476	4502
8	4.2	1.7	7.6	4.0	0.55	0.42	3604	4374
12*	3.9	1.4	6.7	3.4	0.57	0.40	3136	3818

*Fired separately

2. Organic content ≤8% by weight

3. Glass distribution ≥50% (qualitative determination of the samples by microscopic examination)

Specifications for water soluble salts could not be established since test bars did not effloresce.

Laboratory-Scale Tests

Based on the above specifications, about 3 tons of waste glass slimes were prepared for laboratory and semi-commercial scale testing. This 3-ton sample was shipped to Glen-Gery Corporation, Reading, Pennsylvania.

Raw Materials Procedure --

The waste glass slimes were produced by the WGM-I processing method described earlier except that the organic removal circuit of the glass plant used a Wemco reamer jig instead of a screw classifier. Removal of organics by the jig was more efficient than by the screw classifier and waste-glass slimes contained less organics (6-8%) than slimes from the screw classifier (10-15%). The particle size of slime was finer in the jig (1-2%; +100 mesh) than the screw classifier (16-18% +100 mesh).

The size distribution of the sample of waste glass slimes is given in Table 8.

Glen-Gery Corporation sampled 400 lbs from the shipment and sent a 300-lb sample from this to the USBM in Tuscaloosa for laboratory evaluation. The balance was used at Glen-Gery for water soluble determination and fluxing tests.

Clays from the three locations described earlier were used for this test. Chemical analyses and pyrometric cone equivalents of

TABLE 8. SIZE DISTRIBUTION OF WASTE SLIMES USED FOR LABORATORY AND SEMI-COMMERCIAL SCALE TESTS

Particle Size Mesh	Wt %	Cumulative Wt %
-100+200	31.0	31.0
-200+325	11.4	42.4
-325	57.6	100.0

LOI at 800°C - 7.9% by wt
Glass Distribution ≥50%
Microscopic Determination

these clays and waste glass slimes are given in Table 9.

Laboratory Procedure --

Mixtures of Glen-Gery, Michael-Kane and San Valle clays and 10-, 15-, and 20- percent waste glass slimes were tempered in water in a dough mixer and then formed in 1 inch x 1 inch x 7 inch bars by stiff-mud extrusion. After drying at 212°F, 20 bars of each composition were fired to 1850°F, 1950°F, and 2050°F at a rise of 100°F per hour. Five bars of each composition were also fired in the production kilns of the respective brick plants.

Results of Laboratory-Scale Tests --

Table 10 shows the results of Glen-Gery clay with waste-glass slimes. These results show that the 15% addition of waste glass slimes decreased the boil absorption by 34% and increased the compressive strength by 55.7% at 2050°F. Results of test bars fired in the production kilns simulated the firing condition of the laboratory at 2050°F. The effect of lowering the firing temperature by waste glass addition is shown in Figure 3, where the addition of 15% water glass slimes caused a decrease of 45°F at the 8% absorption level.

The firing results on San Valle and Michael-Kane brick mixes did not show any significant effects by the addition of 10-, 15-, and 20-percent waste glass slimes. Our scope of work did not permit us to investigate other additions of waste-glass slimes, additional firing temperatures and the effect of "soaking" on the fired product containing waste glass. Both San Valle and Michael-Kane mixes are "soaked" for long periods, 10 hours and

TABLE 9. CHEMICAL ANALYSES AND PYROMETRIC CONE EQUIVALENT OF CLAYS AND WASTE GLASS SLIMES

Clay	SiO_2	Al_2O_3	Fe_2O_3	K_2O	Na_2O	MgO	CaO	TiO_2	LOI	PCI
Glen-Gery	55.8	22.7	8.4	3.6	0.7	1.1	0.2	1.0	[a]6.0	13
Michael-Kane	54.1	17.1	5.7	3.4	2.4	3.0	2.2	0.9	[a]6.9	2
San Valle	64.3	15.7	3.6	2.4	1.8	1.1	0.9	0.8	[a]5.6	3-4
Waste Glass Slimes	59.4	7.1	3.1	1.2	7.9	1.8	8.6	0.3	[b]7	04-08

[a] 1000°C

[b] 800°C

TABLE 10. RESULTS OF FIRING TESTS ON GLEN-GERY CLAY WITH VARYING ADDITIONS OF WASTE GLASS SLIMES

	Shrinkage %	Boil Absorption %	Soak Absorption %	Saturation Coefficient	Compressive Strength, psi
No slimes -					
1,850°F	0.5	18.0	16.8	0.93	2,575
1,950°	2.3	13.8	13.1	0.95	4,150
2,050°	4.8	8.2	6.6	0.80	7,275
plant run	5.7	8.0	6.5	0.81	6,750
10 percent slimes -					
1,850°F	2.0	15.8	14.7	0.93	3,475
1,950°	3.7	11.5	10.5	0.91	5,350
2,050°	6.5	6.6	4.8	0.73	9,450
plant run	6.7	6.9	4.6	0.67	6,900
15 percent slimes -					
1,850°F	2.5	14.9	13.7	0.93	4,525
1,950°	4.0	11.6	10.4	0.90	6,225
2,950°	6.3	5.4	3.8	0.70	11,325
plant run	6.5	7.1	3.9	0.55	10,100
20 percent slimes -					
1,850°F	2.8	16.4	14.9	0.91	3,150
1,950°	3.5	13.2	11.7	0.89	5,150
2,050°	6.2	7.3	5.6	0.77	10,250
plant run	6.0	8.1	6.1	0.75	9,000

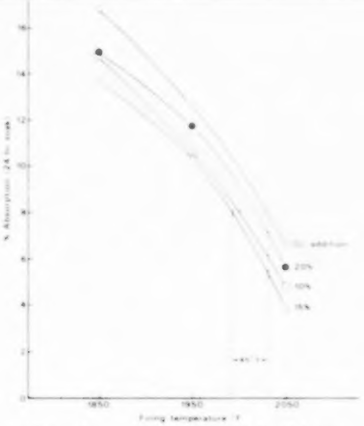


Figure 3. Effect of Slimes Addition on Firing Temperature with Glen-Gery Clay Mix

72 hours, respectively. (The maintaining of the fired product at the final firing temperature is known as "soaking" in the brick industry.) We believe that the lack of data precludes any conclusions in regards to the fluxing ability of waste glass with these brick-mixes containing predominantly clay. We recommend additional research in the area so that the fluxing ability of waste glass with predominantly clay-containing brick mixes can be examined.

Laboratory fluxing tests with 10-, 15-, and 20-percent waste glass additions in the Glen-Gery brick mix were also made at the Glen-Gory Corporation. Results indicated that a 15% addition of waste glass slimes improved absorption by 35% and modulus of rupture by 59%.

Based on the results from the U.S. Bureau of Mines and Glen-Gery Corporation, a 15% addition of waste glass slimes to Glen-Gery brick mix was determined to be most effective.

Semi-Commercial Scale Tests

Shuttle Kiln Procedures --

Standard size solid bricks (2 1/4 inch x 3 5/8 inch x 8 inch) with and without glass were extruded for the tests. The waste glass slimes addition was maintained at about 15% by weight, using premeasured buckets for supplying the glass fraction into the brick mix. Green bricks were made using commercial-scale equipment. The brick mix and waste glass slimes were mixed in a pug mill and formed into standard bricks by extruding the mixture through a die (stiff-mud extrusion) as a continuous extruding column and cut into proper size by a reel-type wire cutter. Bricks with glass contained 15% moisture compared to 16% for bricks without glass.

The extruded bricks were set on wooden skids and placed among the tunnel kiln for preliminary drying. Final drying was done in the shuttle kiln. The semi-dry bricks were set on shuttle kiln cars in a ratio of 2/3 regular bricks and 1/3 bricks with a glass addition.

The bricks were dried in the shuttle kiln for about 36 hours on a small fire (approximately 600°F) and then all burners were lit and the automatic firing control was turned on. The temperature was controlled by four thermocouples; two positioned at the bottom of the kiln and the other two positioned at the top of the kiln. In all, five sets of bricks were fired in the shuttle kiln. Due to thermocouple calibration problems in the shuttle kiln, two sets were also fired in the tunnel kiln with the regular production. Due to inaccurate calibration of thermocouples, an additional two sets, in addition to the original three sets planned, were fired. Tests were planned so that the first set was fired to maturing temperature of the regular bricks; the second set at somewhat lower maturing temperature; and a confirming third set. Again, due to calibration problems, the first three tests at 1900°F, 1800°F and 1930°F did not produce matured regular bricks (8% absorption). After each firing, representative samples of bricks, with and without glass, were selected and sent to McCreath Laboratories (an independent ASTM certified laboratory) in Harrisburg, Pennsylvania for testing. The testing at McCreath Laboratories included cold and boiled water absorption, initial rate of absorption (suction), compressive strength and efflorescence tendency.

Results of Semi-Commercial Tests --

In the shuttle kiln, the 15% addition of waste glass slimes did not significantly affect the strength and water absorption of the bricks except at temperatures of 1950°F and 1970°F, where waste glass addition increased the compressive strength of the bricks by approximately 20%. Interestingly, the results on the two sets fired in the tunnel kiln approached a 33% decrease in boil absorption and up to 76% increase in compressive strength by the addition of 15% waste glass slimes. These bricks, however, showed high degrees of scumming and efflorescence which was not expected and which is not desirable mainly because of the appearance of the bricks.

Scumming and efflorescence are caused by the presence of water soluble salts in the brick mixture. The contents of water soluble salts in the fired product (with glass) and waste glass slimes were 0.35% and 1.14%, respectively. Waste glass slimes contributed approximately half of the water soluble salts contained in the fired brick. The content of water soluble sulfates in the waste glass slimes was 0.18%.

Commercial Scale Tests

The objective of the tunnel kiln test was to demonstrate, in a real plant environment, the feasibility of lowering the firing temperature of bricks by 100°F without negatively affecting the quality of the bricks. Lowering of the firing temperature implies increased kiln throughout and reduced energy cost to the structural clay brick industry.

Approximately 2.5 tons of waste glass slimes containing a low soluble salt content were sent to the Glen-Gery Corporation for testing in the 120,000 bricks per day capacity tunnel kiln. The waste glass slimes were produced in ORC's La Verne pilot plant in a similar way as described earlier except a screw classifier instead of a jig was used for the removal of organics from the glass plant feed. The jig was employed for slimes used in laboratory and semi-commercial tests. These waste glass slimes reported 1.53 percent of water soluble salts (compared to 1.14 percent for jig slimes), 12 percent organics (compared to 8 percent for jig slimes) and 30 percent glass (compared to 50% glass in jig slimes). Glass content of the screw classifier slimes was determiend by sizing it into three fractions and then petrographically analyzing each size fraction.

This 2.5 tons of waste glass slimes were prepared by removing water soluble salts by additional washing on the rotary vacuum drum filter, air drying, screening at 100 mesh and by blending the -100 mesh fraction with -100 mesh glass cullet to bring the glass content to 60 percent by weight of the sample. Currently, all glass flotation plants are using a jig for organics removal and it is expected that the glass content of the jig glass product will contain much higher than 60 percent glass content. The glass content of the USBM, Edmonston, Md. pilot plant jig glass product has been in the neighborhood of 85-90 percent glass. Composition of this sample is given in Table 11 and partical size distribution and chemical analysis is given in Tables 12 and 13 respectively.

Procedure --

The standard size bricks containing 15 percent waste glass slimes were prepared by following the same procedure as used for shuttle kiln tests. $BaCO_3$ was added (0.5 lbs per ton) to the brick mixture to reduce the efflorescence tendency.

In excess of 4000 extruded bricks containing waste glass slimes were distributed on seven kiln cars. The balance of the car capacity was filled with standard size solid bricks without waste glass slimes. A fully loaded car contains 3600 bricks.

The bricks were dried in a tunnel dryer and fired in the tunnel kiln (Figure 4). Cars were moved at the rate of 60 minutes a car length. As the first car approached the firing zones, the burners were turned down to lower the temperature in the firing zones. Heat treatment of the bricks is shown in Table 14.

TABLE 11. COMPOSITION OF WASTE GLASS SLIMES USED FOR TUNNEL KILN TESTS

Composition	Weight Percent
water soluble salts	0.46
water soluble (calcinated @ 1200°F)	0.30
water soluble sulphates	0.035
glass content	60.0
organic (LOI @ 700°C)	6

TABLE 12. PARTICLE SIZE DISTRIBUTION OF WASTE GLASS SLIMES USED IN TUNNEL KILN TEST

Particle Size	Weight Percent	Cumulative Weight Percent
+60 mesh	0.6	0.6
-60+120	3.8	4.4
-120+165	7.2	11.6
-165+200	14.6	26.2
-200+325	23.8	50.0
-325+400	5.6	55.6
-400	44.4	100.0

TABLE 13. CHEMICAL ANALYSIS OF WASTE GLASS SLIMES USED FOR TUNNEL KILN TESTS

Oxides	Weight Percent
SiO_2	63.8
AL_2O_3	4.0
Fe_2O_3	1.7
K_2O	1.07
Na_2O	10.8
MgO	1.44
CaO	9.16
TiO_2	0.26

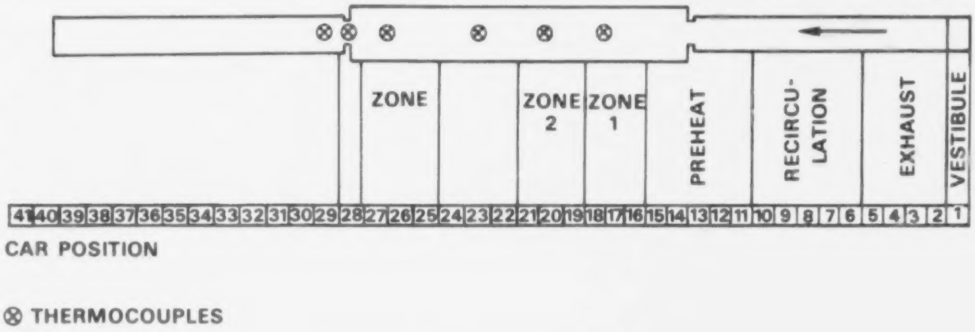

ZONE
ZONE 2
ZONE 1
PREHEAT
RECIRCU-LATION
EXHAUST
VESTIBULE
41 40 39 38 37 36 35 34 33 32 31 30 29 28 27 26 25 24 23 22 21 20 19 18 17 16 15 14 13 12 11 10 9 8 7 6 5 4 3 2 1
CAR POSITION
⊗ THERMOCOUPLES

FIGURE 4. TUNNEL KILN

TABLE 14. HEAT TREATMENT OF EXPERIMENTAL BRICKS

Car No.*	Zone 2			Zone 3			Zone 4**			28	29
59	1680	1660	1665	1720	1720	1720	1835	1820	1810	1805	1820
126	1660	1665	1650	1720	1720	1715	1820	1810	1810	1820	1805
29	1665	1650	1660	1720	1715	1735	1810	1810	1805	1818	1800
100	1650	1660	1680	1715	1535	1740	1810	1095	1800	1810	1805
44	1660	1680	1695	1735	1740	1760	1805	1800	1820	1820	1800
11	1680	1695	1700	1740	1760	1760	1800	1820	1825	1820	1810
29	1695	1700	1705	1760	1760	1775	1820	1825	1835	1830	1820

*Each car contained regular bricks and a few hundred bricks with 15% glass addition.

**During regular production, the temperatures in the fourth zone are maintained between 1900°F - 1930°F.

After the cars came out from the kiln, the bricks were sampled for testing at the McCreath Laboratories in Harrisburg, Pennsylvania. The brick containing waste glass slimes were tested for each car separately, while regular bricks were tested as a composite sample.

The pyrometric cone equivalent (PCE) tests on shale-slime mixtures by the U.S. Bureau of Mines showed a good uniformity in distribution of waste glass slimes in the extruded bricks.

Results of the Commercial Test --

Results from testing the fired brick are compiled in Table 15. Regular bricks with compressive strength 9000 - 11000 psi, boiling water absorption 7% to 10%, IRA 25-35 and with no efflorescence are considered good quality bricks. All the experimental bricks containing waste glass slimes which were fired at 100^{O}F lower temperature were comparable to good quality bricks. Regular bricks which were fired along with glass-containing bricks showed 30% higher absorption and 50% lower compressive strength. Only suction rate and the efflorescence were not satisfactory although the values were of no serious consequence.

TABLE 15. TUNNEL KILN TEST RESULTS

Car No.	WATER ABSORPTION 5 Hr. Boil %	 24 Hr. Cold %	 Satur. Coeff.	I.R.A. (Suction Rate)	Compressive Strength psi	Efflorscence
59	10.0	7.7	0.75	45	9,360	Effloresced
126	10.5	8.0	0.76	47	9,950	Effloresced
19	10.0	7.6	0.75	40	8,560	Effloresced
100	10.4	8.1	0.77	48	9,090	Effloresced
44	9.8	7.4	0.76	39	10,190	Effloresced
11	9.4	7.0	0.74	44	9,630	Effloresced
29	9.1	6.5	0.7	35	10,920	Slightly Effloresced
Composite Sample of Regular Bricks	13.1	11.3	0.86	47	6,670	No Efflorescence

Summary of Commercial Tests --

Firing Time--Because of the lower maturing temperature of bricks containing glass, these bricks can be fired in less time than bricks without glass (1,4,). This means reduced production cost due to increased production rate without any significant additional cost. A typical firing curve for the Reading plant tunnel kiln (used for testing) is shown in Figure 5. The preheat and firing zone temperatures are plotted proportional to time or kiln length, since the charging rate of a tunnel kiln determines the firing time. Although the actual temperatures with respect to time vary from one clay to another, depending upon the impurities and composition of the clay; the curve shown in Figure 5 is also typical for high temperature, red-firing clays.

Figure 5 shows that during firing of regular bricks, the 1800°F temperature is reached within 18 hours contrasted to the 1900°F reached in 24 hours. Allowing for the normal 3-hour hold period, glass bricks will mature in 21 hours, 6 hours less than regular bricks (normal maturing time, 27 hrs.). This is based on the normal charging schedule of one car per hour (24 cars per day) practiced in firing solid bricks at the Reading plant. This would mean that glass bricks can be charged at a rate of 1 car every 46.7 ((21x60)/27) minutes or 30.8 ((24x60)/46.7) cars per day instead of 24 cars per day of regular bricks.

Therefore, potential increase in production using 15% waste glass addition amounts to 22%. This increase would amount to 8.8 million bricks per

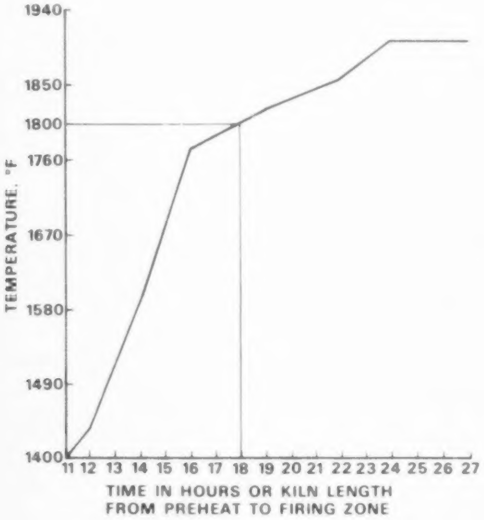


Figure 5. Typical Firing Schedule of Tunnel Kiln Used For Waste Glass Test

year for the Reading plant which normally produces 40 million bricks per year. At an FOB price of $85.00 per thousand, the added production output would increase plant sales by $748,000 per year.

Heat Requirements--The heat requirements of a tunnel kiln depend on many parameters, such as burner type, kiln insulation, percent excess air, stack temperatures, and efficiency of recuperation.

The Reading brick plant consumes 1400 BTU's per lb of solid bricks or 2.8 million BTU's per ton of bricks. The normal daily energy requirement of the Reading plant at 300 tons per day of brick production is 840 million BTU.

Savings in firing time, as calculated earlier by 15% addition of waste glass to clay, amounted to 22%. Therefore, by the addition of glass waste, the heat requirement over the total production will at least be reduced by 22% of by 184.8 million BTU per day, on the basis that incremental bricks did not require any additional work.

ECONOMIC EVALUATION

During this study, a realistic value for waste glass needed to be established by taking into consideration costs of handling waste glass and benefits realized by the utilization of waste glass in brick manufacturing. The basis of the economic analysis was as follows:

o	Conventional Brick Plant Capacity	300 TPD (120,000 Bricks Day)
o	Modified Brick Plant Capacity	345 TPD (138,000 Bricks Day)
o	Glass Product in Brick Mix	15%
o	Quality of Glass Product Used	Air Dry
o	Reduction in Maturing Temp. of Bricks	100°F

This cost/benefit analysis showed that net value of waste glass to a brick manufacturer is $28.10 per ton of waste glass (Table 16). To establish this value, the cost consideration included, capital investment (silos and material handling equipment) and incremental operating costs to the brick manufacturer. The benefit consideration allowed for only a 15 percent increase in production (instead of the possible 22 percent); a brick selling price at $85/1000 (instead of an average price of $112/1000 bricks as determined in the market survey), and an energy savings due to the 15 percent increased production.

In the writer's opinion, the slimes produced at a commercial glass recovery plant can be used in bricks with minimal processing, if any. It is believed that drying may not be necessary for handling purposes and that air dried material can be handled satisfactorily.

A conceptual process flow scheme was developed for dry processing an entire waste glass stream for brick use. Based on the flow scheme, the net cost of producing a glass product, as given in Table 17, was determined to be $13.06 per ton of waste glass (includes a $4 per ton for transporation to brick plant).

TABLE 16. VALUE OF GLASS TO BRICK MANUFACTURERS

Incremental Investment by Brick Manufacturer	$94,000
Energy Savings $/Ton Glass Product (a)	$ 4.85
Credit for Incremental Production (b) (15% More) (c) $/Ton Glass Product	$29.42
Credit for Displaced Clay (d)	$ 0.67
Capitalized Charges @ 26.2% Capital Investment	$(1.37)
Incremental Operating Costs	$(5.47)
Net Value of Glass Product	$28.10

a) Based on 15% Increase in production

b) Bricks assumed to sell at the price of $85/1000 bricks.

c) Incremental production assumed to be 15%. Possible increase in production is estimated to be 22%.

d) Clay assumed to cost the brick manufacturers $5/ton.

TABLE 17. DRY PROCESSING OF GLASS-RICH RESIDUE FOR BRICK USE

o Cost Summary	
Capitalized Charges	$ 4.01/Ton Product
Annual Operating Cost (After By-Product Credits)	5.05/Ton Product
Freight (@ 45 miles)	4.00
Net Cost	$13.06/Ton Product

MARKETING

The market potential for waste glass utilization in structural clay brick manufacture was calculated, taking into consideration the estimated quantities of waste glass available and its location relative to the location of brick manufacturers. The location of brick plants in the U.S. is given in Figure 6. The study results are as follows:

- 45% of resource recovery plants are or will be within 50 miles radius to brick producers (Figure 7).
- Over 90% of resource recovery plants are or will be within 100 miles radius to the brick producers (Figure 8).
- 103 brick customers were contacted; 53 responded. Out of 53 responses:
  - 50 companies made face bricks
  - 40 companies used a tunnel kiln
  - 23 companies used shale or shale-clay mixture
  - average production was 120,000 bricks per day
  - average price was $111.93 per thousand bricks.

CONCLUSIONS

Results of the investigation indicate that waste glass derived from raw refuse is an effective flux for shale body clays. Results were inconclusive on clay body clays. Although bricks showed efflorescence tendency, it was not considered of serious consequence.

Substitution of 15% waste glass for clay reduced the firing temperature by 100°F and produced good quality bricks. More than 4000 glass containing bricks were made in the tunnel kiln. This could mean possibly 22% increase in production of the existing tunnel kiln and a 22% energy savings.

Based on 15 percent increase in production, the value of waste glass slimes to the brick producer was calculated to be $28.10 per ton of slimes. The waste glass slimes can be used as flux in bricks without any additional processing.

The net cost of producing a glass product was calculated to be $13 per ton of waste glass.

The market study indicated that approximately 45% of the waste glass generated by resource recovery plants can be potentailly used by the brick industry.

ACKNOWLEDGEMENT

This research was supported by the U.S. Environmental Protection Agency, Municipal Environmental Research Laboratory under Contract No. 68-03-2469, Mr. Donald A. Oberacker, Project Officer.

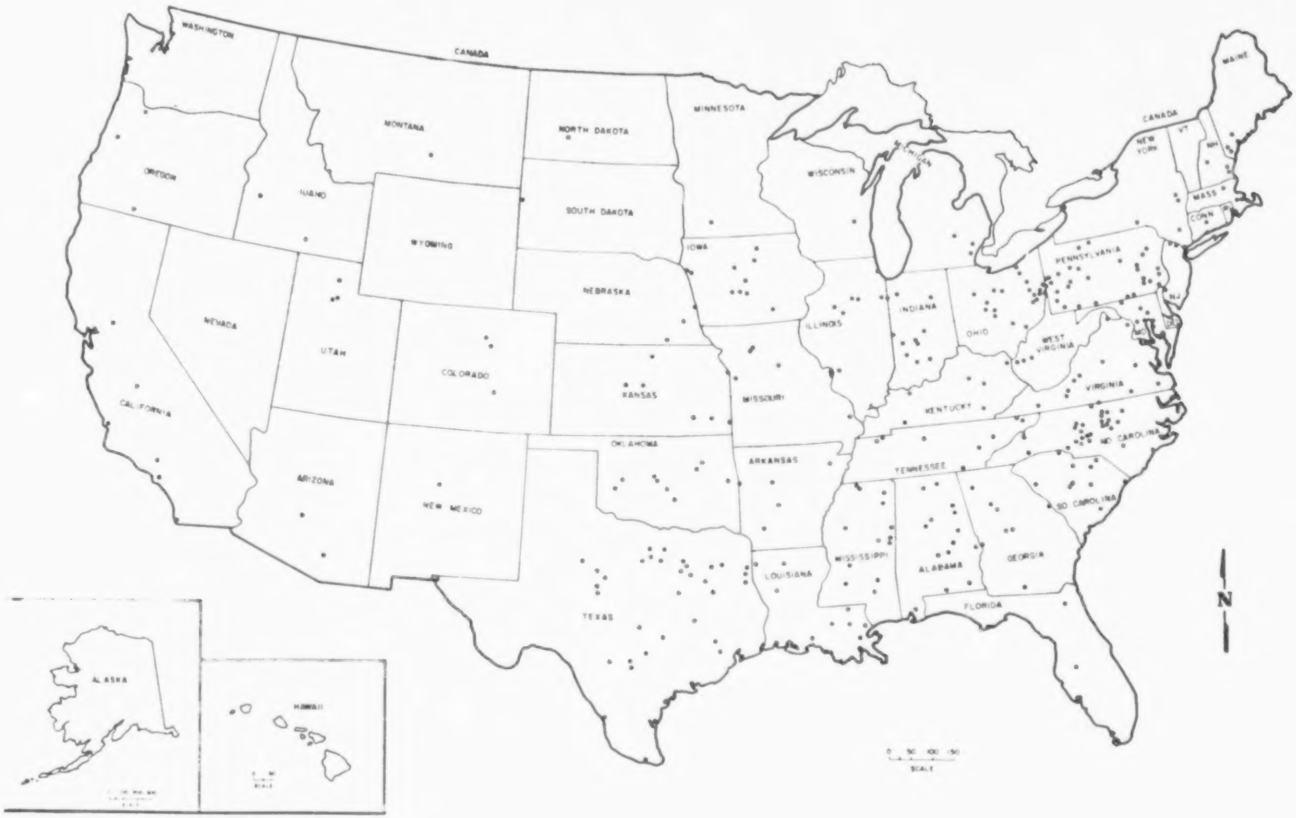

WASHINGTON
CANADA
MONTANA
NORTH DAKOTA
MINNESOTA
OREGON
IDAHO
SOUTH DAKOTA
WISCONSIN
MICHIGAN
WYOMING
IOWA
NEBRASKA
NEVADA
UTAH
COLORADO
KANSAS
ILLINOIS
INDIANA
OHIO
MISSOURI
CALIFORNIA
OKLAHOMA
ARKANSAS
ARIZONA
NEW MEXICO
TEXAS
LOUISIANA
MISSISSIPPI
ALABAMA
GEORGIA
FLORIDA
TENNESSEE
KENTUCKY
WEST VIRGINIA
VIRGINIA
NO. CAROLINA
SO. CAROLINA
PENNSYLVANIA
NEW YORK
NJ
VT
NH
MAINE
MASS
CONN
N
0 50 100 150
SCALE
ALASKA
HAWAII

Figure 6. Location of Brick Plants in the U.S.

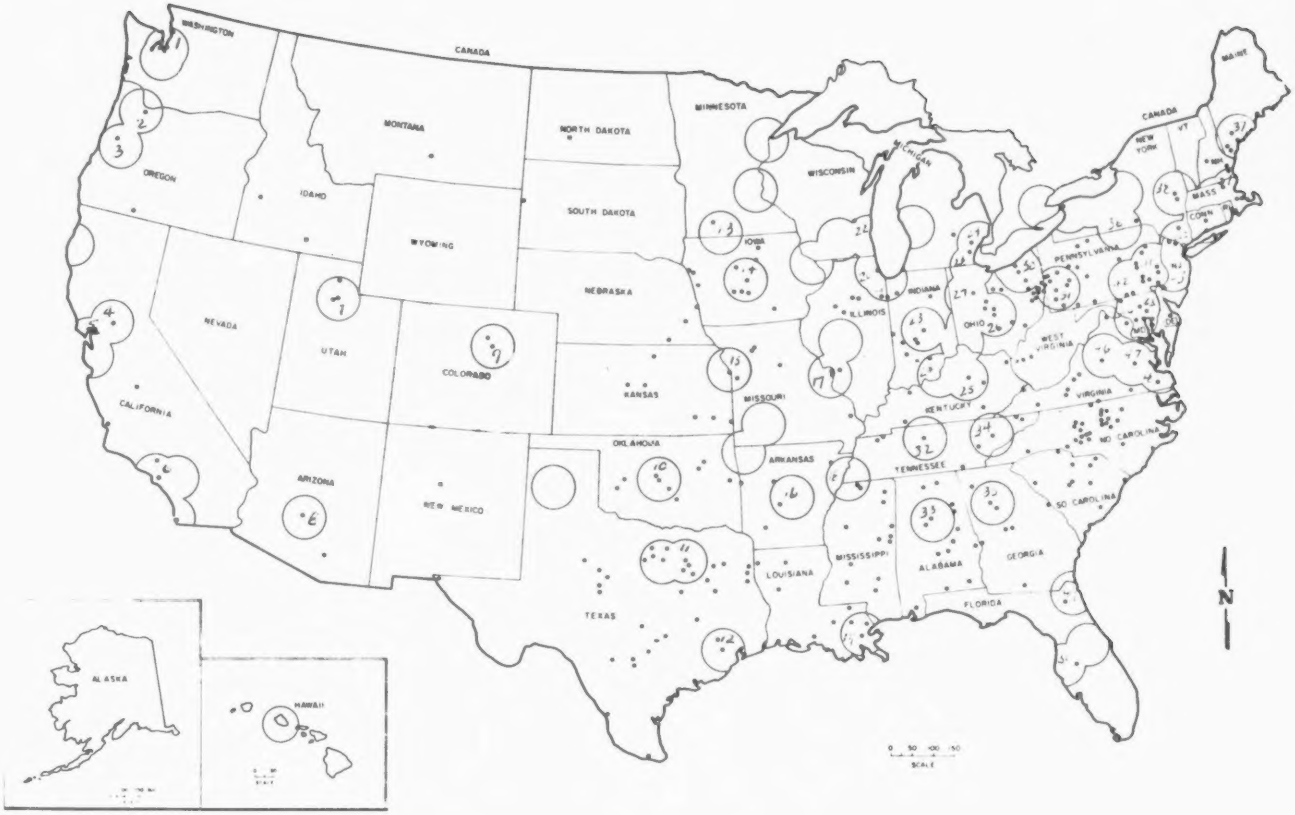

CANADA
WASHINGTON
OREGON
CALIFORNIA
NEVADA
IDAHO
MONTANA
WYOMING
UTAH
ARIZONA
COLORADO
NEW MEXICO
NORTH DAKOTA
SOUTH DAKOTA
NEBRASKA
KANSAS
OKLAHOMA
TEXAS
MINNESOTA
IOWA
MISSOURI
ARKANSAS
LOUISIANA
WISCONSIN
ILLINOIS
MICHIGAN
INDIANA
OHIO
KENTUCKY
TENNESSEE
MISSISSIPPI
ALABAMA
GEORGIA
FLORIDA
SO CAROLINA
NO CAROLINA
VIRGINIA
WEST VIRGINIA
PENNSYLVANIA
NEW YORK
VT
NH
MAINE
MASS
CONN
NJ
MD
ALASKA
HAWAII
N
0 50 100 150
SCALE
1
2
3
4
6
7
9
10
11
12
13
15
16
17
22
23
25
26
27
31
32
33
34
36

Figure 7. Locations of Existing Brick Plants and Existing/Potential Resource Recovery Plants Within 50 Mile Radius

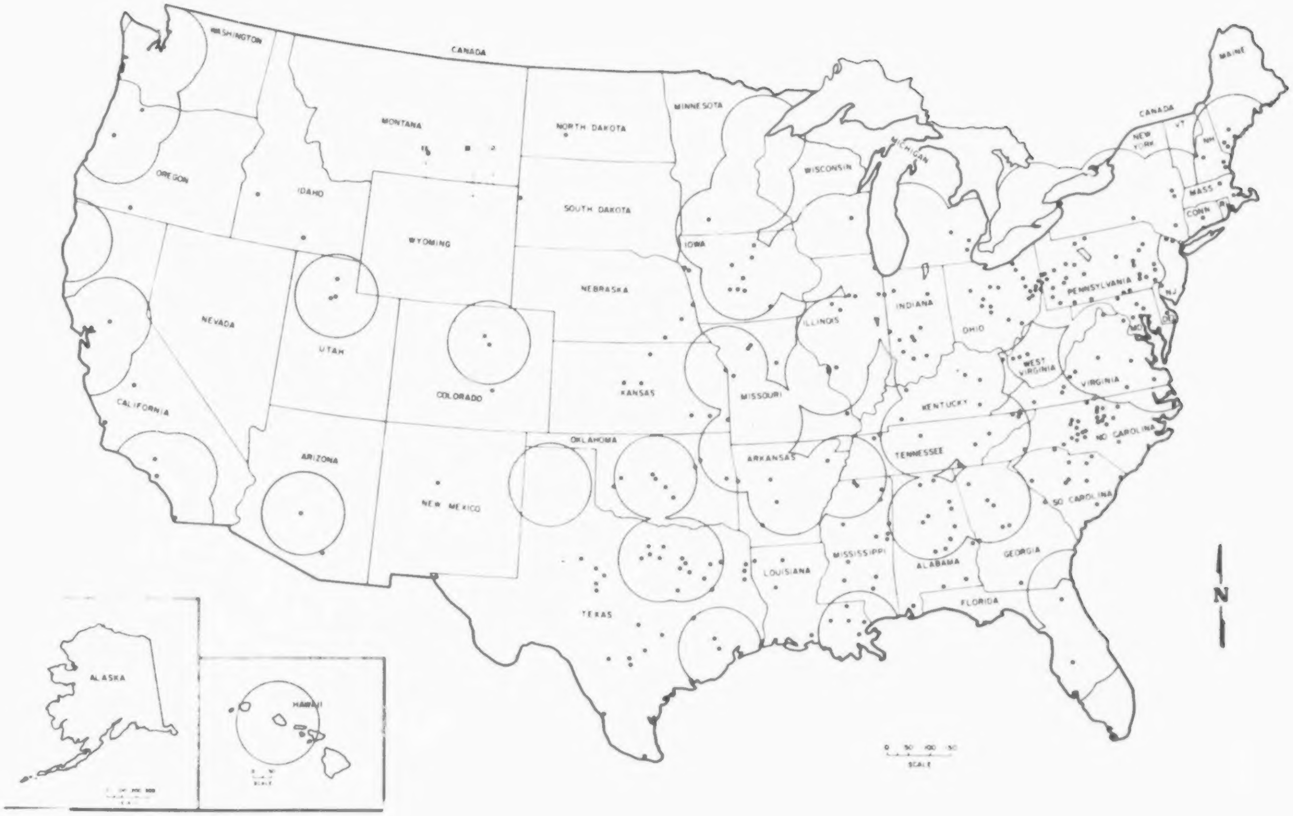

CANADA
WASHINGTON
OREGON
CALIFORNIA
NEVADA
IDAHO
MONTANA
WYOMING
UTAH
ARIZONA
COLORADO
NEW MEXICO
NORTH DAKOTA
SOUTH DAKOTA
NEBRASKA
KANSAS
OKLAHOMA
TEXAS
MINNESOTA
IOWA
MISSOURI
ARKANSAS
LOUISIANA
WISCONSIN
ILLINOIS
MICHIGAN
INDIANA
OHIO
KENTUCKY
TENNESSEE
MISSISSIPPI
ALABAMA
GEORGIA
FLORIDA
SO CAROLINA
NO CAROLINA
VIRGINIA
WEST VIRGINIA
PENNSYLVANIA
NEW YORK
VT
NH
MAINE
MASS
CONN
NJ
CANADA
ALASKA
HAWAII
N
SCALE

Figure 8. Locations of Existing Brick Plants and Existing/Potential Resource Recovery Plants Within 100 Mile Radius

REFERENCES

1. Tyrrell, M.E. and A.G. Goode. "Waste Glass as a Flux for Brick Clays." BuMines Report of Investigation, 7701, 1972.

2. Dr. Gil Robinson's work and comments. Reported by Harvey Gershman in Enclosure I of ASTM E-38.06. Minutes of Philadelphia Meeting, November 11, 1975.

3. Tyrrell, M.E., I.L. Field and J.A. Barclay. "Fabrication and Cost Evaluation of Experimental Building Brick from Waste Glass." BuMines Report of Investigation, 7605, 1972.

4. NCRR Bulletin, Voluem VII, No. 3, Resource Recovery Brief, March 1978.

THE PRODUCTION AND USE OF DENSIFIED REFUSE DERIVED FUEL

Carlton C. Wiles
U.S. Environmental Protection Agency
26 West St. Clair Street
Cincinnati, Ohio 45268

ABSTRACT

As a resource recovery alternative, the use of a densified form of refuse derived fuel (d-RDF) is being investigated as a substitute for coal in industrial spreader stoker boilers. Experiences are summarized from the production of approximately 1700 tons of 1/2 inch diameter pellets using a modified animal feed pellet mill. Storage and other handling experiences are also discussed.

Approximately 400 tons of the d-RDF have been burned in a spreader stoker equipped boiler in a heating plant. A full battery of emissions tests were conducted and observations made to determine the effects on boiler operations. Results of these tests are presented.

INTRODUCTION

The use of refuse as an energy source is a potentially attractive resource recovery alternative. While conversion of the organic fraction of solid waste to liquid or gaseous fuels (i.e., pyrolytic oils, alcohols, methane, etc.) has not been commercially implemented, there are facilities operating today which combust the refuse either directly for steam recovery or in combination with fossil fuels for power generation. The latter involves the processing of the refuse to remove the combustibles for use in a modified power generating boiler, usually in combination with coal. The processed refuse is usually referred to as refuse derived fuel (RDF). Examples of RDF plants in operation are Ames, Iowa and Milwaukee, Wisconsin. These systems, especially Ames, used the experience gained from the St. Louis-Union Electric-EPA refuse derived fuel demonstration project in St. Louis, Missouri. There are other RDF plants in various phases of startup, construction, or design.

The RDF concept in the United States was originally considered primarily for major utilities generating power typically designed to burn pulverized coal. These utility boilers often produce more than 400,000 pounds of steam per hour. The use of RDF, however, does not have to be limited to this larger user and, in fact, may offer more value as a fuel for other smaller power generating facilities, i.e., the small industrial and institutional boiler owner. Many of these boilers are stoker-fed and usually designed to produce 75,000 to 200,000 pounds or more of steam per hour. This is an attractive alternative. One reason for this involves the inability of the smaller fossil fuel user to receive quantity discounts for purchase of primary fuel. He therefore pays higher prices for his coal as compared to the larger utility. In this instance, the RDF may have a higher dollar value to him, which in turn results in a higher return to the resource recovery facility producing the RDF. Another reason involves the expansion of the potential market area for the RDF to smaller communities that today cannot afford recovery of refuse as RDF for a larger utility user. Other marketing factors such as increased flexibility in contract negotiations, especially in length of commitment, may also increase the attractiveness of the smaller user as a market for RDF. Additionally, there are a greater number of these small power generating boiler facilities (as compared to the larger utilities) located in both large and small communities. Many of these coal burning units are older, prior to 1940, because newer ones were built or converted to use oil or gas. The use of RDF in these facilities, many of which are economically marginal, may help to reduce the impact of costly air pollution control equipment.

Refuse derived fuel prepared for the larger utility boilers is typically the light fraction of shredded refuse which has been air classified, screened, or otherwise processed to remove the noncombustibles. In this fluffy form it can be pneumatically fed into the suspension utility boiler. In contrast, a densified form of RDF is probably more desirable for use in the stoker fed boilers. This densified refuse-derived fuel (d-RDF) may approximate the physical characteristics of the stoker coal fed to the boiler. This offers the possibility of increased flexibility in transporting, storing, and otherwise handling the RDF. Of major importance in this respect is the potential capability of mixing the d-RDF directly with the coal for feeding to the boiler with only minor or no modifications required.

The Municipal Environmental Researcn Laboratory (MERL) in Cincinnati has major EPA responsibility for R&D in the recovery and utilization of municipal solid waste materials. Naturally, programs have included the recovery of energy from solid waste. This would appear to be the most attractive resource recovery alternative available today. It is an alternative that could provide a return sufficient to yield an economically successful plant, while helping to solve the real problem of solid waste disposal.

While experiences with RDF use were available and being added to, little information was available on d-RDF, especially concerning its production. Therefore, EPA implemented a program to investigate the technical and environmental aspects of producing and using d-RDF. If proven to be technically and economically feasible and environmentally acceptable, the use of d-RDF may be an attractive resource recovery option for many communities. This paper summarizes the EPA d-RDF program and presents results of studies conducted thus far.

EPA PROGRAM IN d-RDF

Although this paper will discuss EPA's d-RDF program, it is not intended to imply that the concept originated with EPA. There have been a number of trials of burning densified forms of waste materials. However, despite these successful trials, little testing results and operational experiences are available. EPA considered that for the use of d-RDF to become widely implemented a credible experimental program was needed to establish the environmental acceptability and show that the concept is economically and technically sound. Of major importance is the effects on boiler physical facilities, boiler operations, and the environment from burning the d-RDF. The EPA program objective is to provide the necessary experimental data and operational experiences to interest potential users to implement the concept. More specific objectives can be summarized as follows:

o To establish the equipment modifications necessary to utilize d-RDF in existing stoker-fired boilers. Modifications might well include changes in fuel feed devices, grate speed controls, overfire and underfire air, and dust collectors. The necessary modifications should be specified as a function of the boiler type. Hopefully, experiences will show that only minimal modifications will be required.

o To establish the characteristics of the d-RDF required for combustion in stoker-fired boilers. These must also be established from a materials handling viewpoint. Properties of interest are the size and shape of the densified fuel, its density, its moisture content, its mechanical strength, and its constituents. Refuse processing required to produce a specification d-RDF will require study.

o To establish the operating conditions necessary for a stoker-fired boiler burning coal and d-RDF. These conditions will include coal-to-refuse ratio, air distribution (primary to secondary), air temperature, excess air, and other characteristics.

o To establish the influence of d-RDF on the boiler performance. Information is needed to determine effects on boiler efficiency, efficiency of dust collection and other emission control equipment, and associated factors such as fouling and corrosion.

o To establish the environmental impact from the use of d-RDF. Influences on air emissions, ash quantities and quality, water emissions where applicable, and similar factors must be determined. The fate of trace compounds is also important.

o To establish the economic impact of burning d-RDF. This involves not only the impact on the user facility, but an estimation of the potential economic impact of d-RDF as a solid waste resource recovery alternative for a community. Cost of producing a specification d-RDF will have a major impact upon the economics of a d-RDF system.

Briefly, the program involves four projects. Initially, two concurrent projects were implemented.

o A research grant was awarded to the National Center for Resource Recovery (NCRR) to study production requirements for d-RDF. The establishment of production costs and characteristics of a specification d-RDF were considered important. Material handling during production, transport, storage, and use were also important. Additionally, NCRR was to produce d-RDF for combustion tests.

o A competitive contract was awarded to Systems Technology Corporation to establish the combustion characteristics of the d-RDF and its effects on boiler performance, environmental impact, and other factors associated with the use of d-RDF.

o Later in the program, a second research grant was awarded to the University of California. This project is supplementing the NCRR grant in looking at the basic theoretical aspects of producing and using d-RDF.

o More recently, in an effort to make more meaningful test burns, a contract was awarded to Teledyne National to produce 2000 tons of d-RDF. The production is being done at the Cockeysville, Maryland resource recovery plant. This project will also provide additional information on production processes.

Information presented in this paper is based upon experiences gained thus far from conduct of these projects. Approximately 1700 tons of d-RDF have been produced. Of this approximately 400 tons have been combusted with coal in stoker boilers. Additional combustion tests are being implemented.

PRODUCTION, HANDLING AND STORAGE CONSIDERATIONS

PRODUCTION

Considerable experience has been gained in the production of d-RDF. Since 1976, the National Center for Resource Recovery, Inc. (NCRR) has pelletized approximately 1400 tons, including approximately 100 tons of 1-inch diameter pellets. Three hundred tons of pellets were produced in late 1976 through the Spring of 1977 for combustion tests at Hagerstown, Maryland (Figure 1). This process was modified by installing a zig zag air classifier (in place of the "Vibrolutriator") which was fed with a large vibratory feeder. This was done in an attempt to provide a cleaner feed to the pellet mill and thus reduce die and roller wear and reduce ash content of the d-RDF. After these modifications, an additional 1100 tons of d-RDF were produced. Properties of the d-RDF are summarized in Table 1. The NCRR processes were limited because of space and equipment considerations but can be used to illustrate a process flow. The production run currently being made by Teledyne will provide information on a modified process using a trommell to screen the air classified light fraction prior to secondary shredding. This process is expected to provide a cleaner feed to the pellet mill and thus result in a lower ash d-RDF. Appropriate production and use experience will determine if this happens.

Most data and observations presented are based upon the NCRR production.

Feedstock Preparation

The preparation of the feedstock to the pellet mill is important, as its condition may have the most significant impact upon pellet mill performance and product quality. The process used at NCRR resulted in problems caused by textiles. Although 95 percent of the feed may be minus 1-1/4 inch, textiles predominate in larger sizes, generally 2 to 4 inches. The textiles are difficult to shear through the pellet mill die and tend to bunch up behind the rolls and slip until the pad breaks loose and causes the machine to jam.

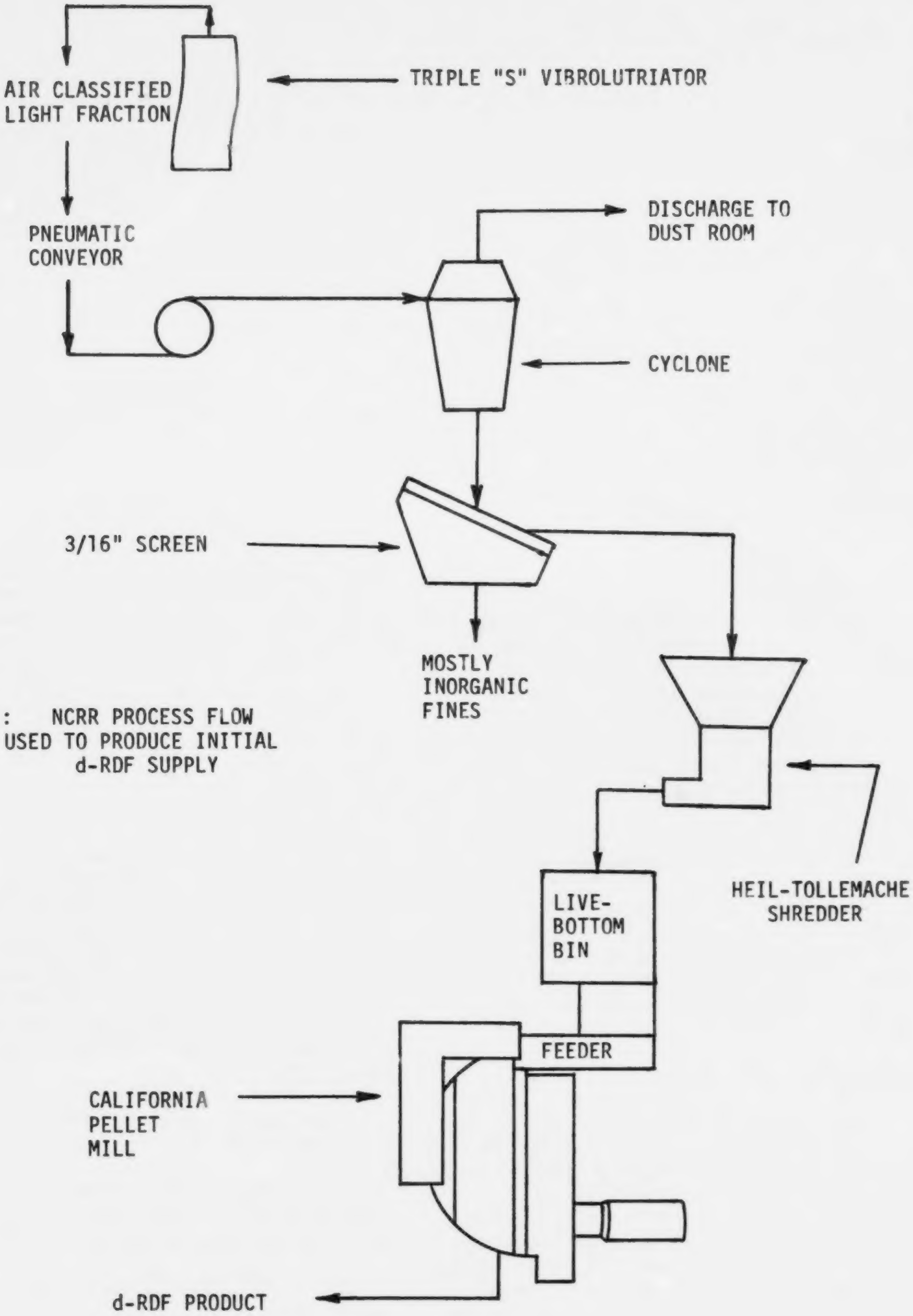

AIR CLASSIFIED
LIGHT FRACTION
TRIPLE "S" VIBROLUTRIATOR
PNEUMATIC
CONVEYOR
DISCHARGE TO
DUST ROOM
CYCLONE
3/16" SCREEN
MOSTLY
INORGANIC
FINES
HEIL-TOLLEMACHE
SHREDDER
LIVE-
BOTTOM
BIN
FEEDER
CALIFORNIA
PELLET
MILL
d-RDF PRODUCT

Figure 1: NCRR PROCESS FLOW USED TO PRODUCE INITIAL d-RDF SUPPLY

TABLE 1

d-RDF PROPERTIES AS PRODUCED AT NCRR

	1/2"		1"
	Fall, Spring 1977	Fall 1977-Fall 1978	June 1978
Moisture (%, D.W.)	19.1	22.9	22.8
Ash (%, D.W.)	26.6	23.4	22.8
-3/8" Fines (%, A.R.)	N/A	14.9	9.6
Pellet Density (g/cc)	1.17	1.01	0.76
Bulk Density (LB/CF, A.R.)	38.6	35.9	27.0
Mean Length (mm)	17.9	15.9	N/A

The particle size distribution (PSD) of the nontextile feed is not as significant a factor as the textiles. Other types of size reduction equipment such as knife shredders will provide better control of textiles. These, however, may have problems from relatively narrow tolerances, sensitivity to tramp metals and inerts, and higher maintenance costs.

Schemes to screen the light fraction to remove inerts, bypass undersize material around the secondary shredder and concentrate the textiles in smaller fraction would seem to be an easy way to alleviate some of the operational and maintenance problems of the NCRR approach. The production run at Teledyne may yield some of this information.

Densification

Actual densification of the refuse was done in an animal feed mill built by the California Pellet Mill Company (CPM). The mill channels input materials between a rotating 33 inch, i.d., 49 inch o.d., die and two stationary rollers which force the feed through the die holes. The die rotates at 170 rpm and is driven by a 150 horsepower motor. Both 10 and 13 inch diameter rolls were utilized, with 85 percent of the 1976-77 production on 10-inch rolls and virtually 100 percent of the 1977-78 production on 13-inch rolls. While the larger rolls improved reliability, no impact on pellet properties was apparent. Dies with 1/2-inch hole diameters were used except during June 1978, when an alternate die with 1-inch diameter holes was tested. Die selection was dictated by the objective of making pellets replicating stoker coal properties.

Application of the pellet mill to MSW uncovered problems with capacity, operational reliability, and maintenance that were unexpected or inexperienced in the widespread applications to agriculture, animal and wood product wastes. One reason for this relates directly to the differences in feedstock and machine operations with the solid waste as compared to the machine's normal use.

Following are important examples of these differences:

o The particle size (PSD) of the feedstock is smaller than the die opening on all applications except for MSW.

o The MSW feedstock density at 2-4 pounds per cubic foot (pcf) is only half that in most other application.

o The feedstock moisture in other applications is maintained at lower or more uniform moistures of 12 to 15 percent by drying or steam addition.

o The inert and tramp metal levels in other feedstocks do not approach that of MSW.

o The pellet product is cooled and screened to remove the fines for recycling in most applications. Cooling apparently aids the integrity of the pellets.

Regardless of these differences, pellets can still be produced from sized MSW light fraction over a range of throughputs, moisture, particle size (excepting textiles) and inert levels.

Production expectations of 10 tons per hour of 1/2-inch diameter d-RDF pellets were not realized with the pelletizer. Experiences with the 1/2-inch die indicate that 5 tons per hour is the maximum throughput achievable with this mill, while most production was at lesser rates. One reason for this would be the difference in the actual MSW feedstock density (2-4 pcf) compared to 7 to 9 pounds per cubic foot presumed by the manufacturers. Higher capacities may be achievable with larger diameter pellets and cleaner feedstocks (i.e., less of textiles and inerts) with smaller, more consistent particle size distributions.

Cost of producing the d-RDF is expected to have a significant impact upon the economics of the d-RDF concept. Die wear of the pelletizer was expected to be important because of costs associated with repair or replacement.

For the material and inert levels at NCRR, the die life was on the order of 1000 tons and the roller life 500 tons. However, since the inert concentration was much higher than necessary, it is difficult to extrapolate these findings. By controlling the inerts to 8 to 12 percent, the investigators estimate a production life of 3000 tons on the die and 1500 tons on the rollers. A further complication in projecting costs for die and roller replacement is that the die may be re-tuned and the roller shells alone replaced, thus postponing full replacement costs.

Although in operation only briefly, to produce approximately 100 tons, the 1-inch die seemed more tolerant of oversize textiles. The 1-inch pellets produced had lower densities than the 1/2-inch pellets. This is probably attributable to the taper of the die used and thus could be improved by using a die with more taper.

Because the densification, and especially the throughput of the densifier, will have a significant impact upon economics of d-RDF, additional work with various densifier designs is needed. There is now, however, considerable experience available to aid this work. Additionally, better information is required to determine exactly what the d-RDF has to be for acceptable use in the boiler, since this will help determine the amount of production processing required.

HANDLING AND TRANSPORTING

Pellets produced at NCRR were trucked to Hagerstown, Maryland (approximately 75 miles) in 20 cu. yd. drop boxes. Boxes were covered. Shipments from D.C. to Erie, Pennsylvania where Phase 2 testing will take place were made in dump trucks. No apparent problems have been experienced. Care must be exercised, however, to ensure that container beds be clean of trash, or other materials which might contaminate the d-RDF. Containers should also be properly covered to prevent blowing of the material and/or wetting of the d-RDF.

Movement of the d-RDF from storage for loading or other reasons has normally been by front-end loader or similar equipment. Blending with the coal at Hagerstown and movement to the existing coal weigh lorry was done with a system consisting of 2 hoppers, 2 belt conveyors, and a bucket elevator which discharged into a chute feeding the lorry. As a precaution, this was used instead of the plant's only existing coal silo system. After proper adjustments, the system operated well to blend the coal:d-RDF and to feed the lorry. This indication that the coal:d-RDF blends can be handled by existing plant equipment has been verified in preliminary trials at the Phase 2 test site and will be further confirmed during detailed testing.

The major problem experienced with the d-RDF at the boiler plant was dusting. Appropriate precaution to control dusting will be necessary in normal operations.

STORAGE OBSERVATIONS

Storage of d-RDF will be an important consideration in production and use. Production schedules have not corresponded to combustion tests schedules for various reasons; one of which involved delays in obtaining a test boiler. This circumstance provided good opportunities to observe the reactions of the d-RDF to various storage regimes. Storage has occurred at four different locations; Washington, D.C., Hagerstown, Maryland (2), and Erie, Pennsylvania.

Hagerstown Storage

d-RDF storage for the Hagerstown test involved both indoor and outdoor storage over approximately 2 months. Storage procedures utilized were based upon those recommended for lignite coal, i.e., keeping storage periods as short as possible and pile depths to no greater than 6-8 feet. The d-RDF storage in the warehouse resulted in no apparent problems, although what appeared to be fungal growth did take place on the surface of the 6-foot piles. Some mildly offensive odors were also noted, but no rodent damage was observed.

Additional storage at Hagerstown was done by piling the d-RDF pellets 6-7 feet high onto a concrete pad. The pellets were covered with a plastic tarpaulin. During storage, moisture released from the pellets accumulated on the undersurface of the plastic and wetted the surface of the d-RDF pile. This moisture caused pellet deterioration and caking, but only at the surface of the pile. Pellets exposed to the excess moisture swelled to cause some minor material handling problems.

Although limited storage of pellets in 20 cu. yd. drop boxes caused pellets to freeze near the edges, they were easily broken and caused little difficulty.

Washington, D.C. Storage

After the Hagerstown burn tests, the program was to proceed to a second phase test burn in a larger more typical boiler. Because of problems encountered in locating and arranging an acceptable site, pellets produced by NCRR had to be stored near the production site. Precaution dictated that the storage be outside. Storage was expected to be short term, but as the difficulties in locating a second phase test site mounted, delays pushed the storage into months. Observations made during this storage are interesting.

The original storage plan, dictated by the expected short term and non-permanent nature of the storage requirement, involved the following:

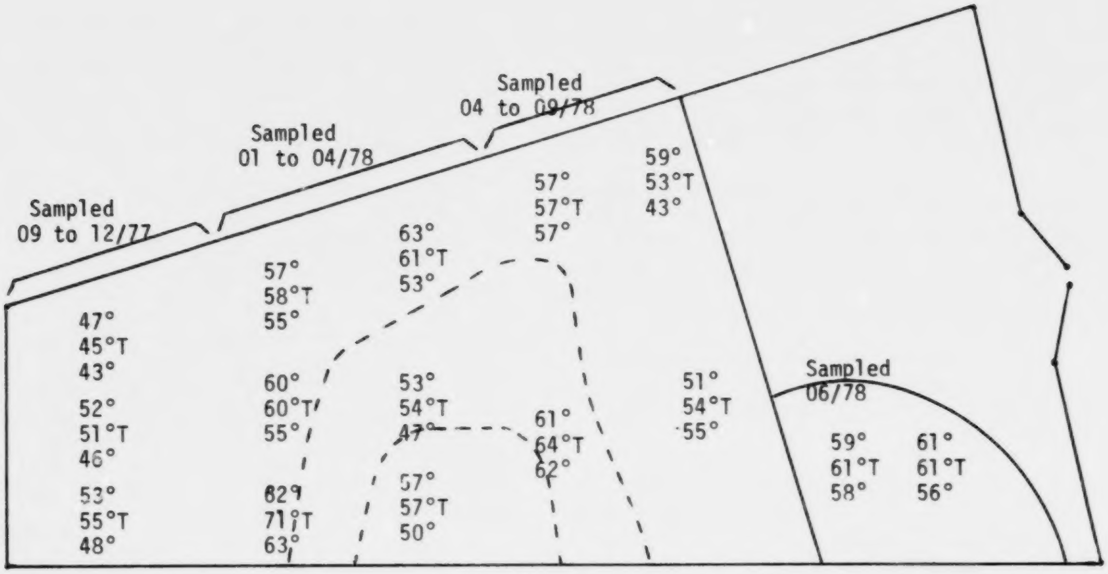
- o 1/4 acre sloped asphalt pad;
- o 6 foot high contained pile;
- o plastic tarp cover anchored by tires to keep water out and prevent blowing material;
- o placement in the pile of net bags of pellets of known properties; and
- o measurement of temperatures to assure there was no tendency toward spontaneous combustion.

As observed at Hagerstown, the covers provided a surface on which moisture generated from inside the pile would condense and rain back down on the surface. Moisture levels within the wet cap that formed over the entire pile reached 130 percent dry weight or saturation. Although it was felt leaving the pile uncovered may have been preferable, concern over blowing paper was overriding and the plastic tarps were continued.

Temperature monitoring showed a random pattern by depth and location with a range of 40 to 70°C, nothing above that expected from biological degradation (Figure 2).

Seven months into storage and with no problems apparent, the height of the pile was increased in some areas to 10 to 15 feet. This was dictated by the need for more storage capacity. In the process, a portion of the wet cap was covered and the material thoroughly aerated. As to whether this event triggered later more active biological and/or chemical activity is not known, but suspected.

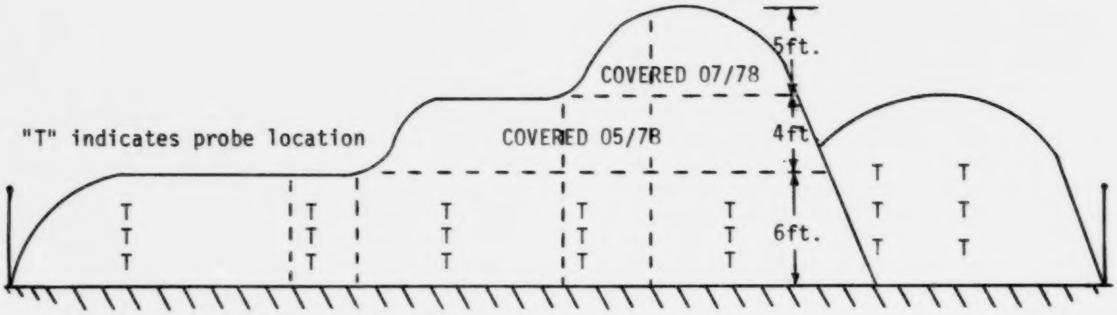
After this event and during the summer months, temperature profiles near the


Sampled 09 to 12/77
Sampled 01 to 04/78
Sampled 04 to 09/78
Sampled 06/78
47° 45°T 43°
52° 51°T 46°
53° 55°T 48°
57° 58°T 55°
60° 60°T 55°
62° 71°T 63°
63° 61°T 53°
53° 54°T 47°
57° 57°T 50°
57° 57°T 57°
61° 64°T 62°
59° 53°T 43°
51° 54°T 55°
59° 61°T 58°
61° 61°T 56°

TOP VIEW

Mean °C at Top Probe Location
Mean °C at Middle Probe Location
Mean °C at Bottom Probe Location

Highest Probe Temperature- 90°C(surface)
Lowest Probe Temperature- 38°C(base)


"T" indicates probe location
COVERED 07/78
COVERED 05/78
5ft.
4ft
6ft.
T T T

SIDE VIEW

Figure 2: LOCATION OF TEMPERATURE PROBES AND TEMPERATURES RECORDED IN d-RDF STORAGE PILE

top increased with maximums of 85 to 90°C. In August, 10 months into storage, a series of smoldering seams of pellets with temperatures above 150°C and hot enough to ignite plastic or tires surfaced in an area where the pellets had been repiled. Excavations and measurements provided a great deal of data but yielded no conclusive explanation:

o Whereas the as-produced moisture varied from 15 to 35 percent, seams of pellets with from 4 percent to 131 percent moisture were uncovered. They ran generally horizontally through the pile at varying depths and thicknesses (Table 2).

o The hot smoldering seams were randomly located, often not connected and adjacent to both very wet and very dry materials.

o The mulch smell, darkened color and increased levels of fines in many parts of the pile indicated that it had composted.

o The smoldering, charred seams extended back into portions of the pile that were still at the original 6-foot depth, but were more extensive in the repiled portions.

o While the angle of repose of the as-produced pellets was 35 to 70°, when the stored pellets were excavated, they often formed stable walls at 90° or more.

These episodes naturally raise questions as to the cause and to what extent the particular production, handling, and storage techniques may have contributed to the problem. Predictive schemes for the reactive mechanism(s) involved are impossible to develop for such a heterogenous material. Possibly brought on by the aeration and increased moisture of repiling, increased biological decomposition provided sufficient activation energy to trigger a chemical reaction and subsequent higher enthalpies from chemical decomposition. These hot seams would dry adjacent pellets and then ignite and begin to oxidize them.

The extended storage and handling necessitated by the smoldering naturally caused pellet deterioration. Fines were significantly increased. By this time a second phase burn test site had been identified in Erie, Pennsylania. In order to verify that the d-RDF would be useable for the tests, approximately 60 tons (4 truck loads) were shipped to Erie and burned. Despite the deteriorated conditions and relatively large fines content, the test was extremely successful. The plant officials witnessing the day's operation indicated minor problems of some odor and dusting.

The remaining NCRR pellets were shipped to Erie, Pennsylvania for test burning in January-February 1979. Thus, some of the pellets will have been in storage for over 12 months at the time of use. Observations will continue. Additionally, the Teledyne pellets will be stored in Erie, Pennsylvania, prior to a separate test burn. The storage will be for much shorter periods. Comparison of these pellets and their condition with the NCRR pellets during combustion will be important. The information will help better define what "d-RDF" must be for acceptable use.

Although there is little doubt storage, and particularly the handling in and out of storage, will increase fines and reduce pellet length, density and bulk density, the result should never approach what was observed in this program. First, storage beyond four weeks in a commercial operation will probably not be necessary and the effect of less than a month's storage will be minimal. Second, proper storage conditions including shallow piles and a ventilated cover will minimize the chance of degradation. Third, screening and cooling the pellets as they are produced will probably make them more resistent to deterioration.

COST CONSIDERATIONS

Costs associated with producing d-RDF are uncertain and are still being developed. Factors to be considered include densifier die and roller wear, equipment maintenance requirements, the amount of refuse preprocessing required prior to introduction into the densifier, and the final characteristics required for an acceptable d-RDF.

Cost will, of course, be greatly dependent upon throughout capacities of the densification equipment. It is evident that the pellet mill used at NCRR could not meet expected capacities. However, much operating experience was gained which can be used to improve future production facilities. Additionally, alternative densi-

TABLE 2

SUMMARY OF d-RDF STORAGE PILE DATA
August 25-September 1, 1978

Sample	Description/Prevalence	Temp.	Moisture	-3/8" Fines	Mean Length
1	1 ft. from base-bagged sample - 21 wk. in pile	65°C	57%	27%	8.8 mm
2	4 ft. from base-bagged sample - 21 wk. in pile	N/A	32%	7%	11.3 mm
3	6 ft. from base-bagged sample - 21 wk. in pile	N/A	4%	8%	10.8 mm
4	Oxidized, friable mat'l - reddish brown - very localized in pockets	75°C	5%	31%	9.4 mm
5	Light brown - typical of 70-80% of central pile	68°C	18%	23%	9.4 mm
6	Prevalent light brown material along side slope	40°C	6%	15%	10.9 mm
7	6-inch thick white strata overlaying #6	44°C	17%	12%	9.5 mm
8	6-inch thick dark strata overlaying #7	58°C	131%	36%	7.1 mm
9	Localized wet dark brown strata	75-85°	47%	35%	7.5 mm
10	Localized wet black strata - crumbly		44%	45%	6.3 mm

fication equipment has not been thoroughly tested with MSW.

Thus far, work has shown that the pellets can be satisfactorily handled in existing boiler equipment. Some modifications to stoker feeders and other equipment may be required but are expected to be minor. The costs associated with use of the d-RDF in power generating facilities are also being developed.

USE OF d-RDF IN COMBUSTION TESTS

The objectives of the combustion tests involved determining the effects of burning d-RDF (with or without coal) on the boiler, its operation, associated facilities and equipment, and the environment. Information, data, and observations discussed are based primarily on the experimental combustion tests conducted at the State of Maryland Correctional Institute for Men, located near Hagerstown, Maryland. The boiler plant consists of a battery of three 150-psig Erie City boilers. Their design steam ratings are 78,500, 60,000 and 25,000 lbs/hr. Each unit is equipped with Hoffman Combustion Engineering "Firerite" spreader stokers to distribute the lump fuel in the furnace. The large coal pieces that do not burn in suspensions, are combusted on the surface of Hoffman vibrating grates, and ash is discharged to the front.

The Erie City boilers have the tube-and-tile furnaces. The water-walls are composed of wide-spaced nominal 3 1/4-inch diameter tubes that were later partially embedded in refractory to approximately 8 feet above the grate. The gases are exhausted from the furnace through a two-drum boiler bank, consisting of rows of 2 1/4-inch diameter tubes, with two gas passes. The flue gases are cleaned in a two-stage multiclone collector. The fly ash gathered in the first-stage collector is reinjected into the boiler to complete combustion of the fly char, and the fly ash in the second-stage collector is pneumatically transported to disposal. The cleaned gases are induced through a centrifugal fan and exhausted to a common breeching and stack.

Approximately 280 tons of d-RDF were burned at the Hagerstown test site. Table 3 presents properties of the d-RDF as used at the site. The following summarizes the length of combustion testing for the various blends:

Blend Ratio (coal:d-RDF)	Length (hours)
1:1	58
1:2	53
0:1	29

Properties of the blends used in the May tests are shown in Table 4. During the May tests, one boiler was continuously fired with coal:d-RDF blends (141 tons of d-RDF) for a period of 132 hours. Boiler loads were varied between approximately 17 and 53 percent of boiler load rating. The test program was designed to acquire three replications of emissions data for each blend. Periods for boiler stabilizations on each blend were reduced as were other observations because of the limited supply of d-RDF available for testing.

BOILER PERFORMANCE

Tests were conducted and observations made to measure the effects of d-RDF:coal blends on boiler operations. These included d-RDF cold flow and hot flow tests; observations of effects on boiler operations; effects on ash handling system; air and gas handling; fouling, slagging, and wastage; boiler control requirements; mass and energy balances; and others. Observations are summarized.

Cold Flow

Tests showed that the d-RDF could be satisfactorily fed to the boilers through the existing feeders at settings normally used for coal firing. Fuel distribution patterns were acceptable with the d-RDF being fed to the desired furnace locations. The spreader performed as designed in that the largest pellets with the greatest mass travelled to the rear of the boiler with the fines falling closest to the spreader.

Hot Flow and Blend Testing

Prior to blend testing, approximately 1 ton of 1/2-inch diameter pellets were fired without coal to help determine limitations on boiler performance. It was necessary to adjust the fuel trajectory to prevent fuel and flame impingement on the rear wall. Shortly after starting, the steam pressure decreased from approximately 153

TABLE 3

AVERAGE d-RDF PROPERTIES ON AN AS-RECEIVED AND A MOISTURE AND ASH FREE BASIS AS USED IN THE HAGERSTOWN TEST BURNS

	December Average	March Average	May Average	December Average	March Average	May Average
As Received						
% Moisture	13.4	12.62	12.22	MOISTURE & ASH FREE		
% Ash	19.97	24.41	28.75			
% Volatile	56.54	54.08	49.27	85.04	85.80	83.38
% Fixed C.	10.1	8.89	9.76	14.97	14.21	16.62
Btu/Lb.	6488	5534	5266			
Dry Basis						
% C	43.98	39.17	35.63	54.29	54.42	53.36
% H	5.29	4.47	4.54	6.53	6.20	6.75
% N_2	.35	.39	.85	.43	.54	1.25
% Cl	.40	.45	.36	.49	.62	.54
% S	.40	.26	.28	.53	.36	.42
% Ash	23.19	27.97	33.02			
% O_2	30.80	27.30	25.33	38.02	37.87	37.68
Btu/Lb.				9785	8772	8956
Fusion						
Initial	2018°F	2040°F	2005°F			
1st Softening	2088°F	2103°F	2105°F			
2nd Softening	2175°F	2155°F	2125°F			
Fluid	2275°F	2215°F	2225°F			
Mineral Analysis						
Phos. Pent. Ox	.87	.73	.65			
Silica	55.52	71.58	63.65			
Ferric Ox.	2.27	2.89	2.64			
Alumina	13.45	4.43	8.39			
Titania	.66	.99	.69			
Sodium Ox.	6.82	5.66	7.53			
Potassium Ox.	1.30	.53	.91			
Lime	10.75	7.50	9.74			
Magnesium	1.14	1.12	1.59			
Sulfur Tri Ox.	6.03	1.22	3.20			
Undetermined	1.19	1.87	1.00			

TABLE 4

PROPERTIES OF THE COAL:d-RDF BLENDS USED IN MAY*

			AS FIRED	
VOLUMETRIC BLEND	1:0	1:1	1:2	0:1
PARAMETER				
Moisture*	1.3	6.6	7.9	16.6
Volatiles	22.6	31.7	38.3	48.6
Fixed Carbon	54.2	38.4	29.1	9.0
Ash	22.0	23.3	24.7	25.9
Btu/lb	11706	8988	8382	5130
MJ/kg	27.2	20.9	19.5	11.9
Carbon	66.5	54.1	47.3	30.9
Hydrogen	4.3	4.1	4.1	3.8
Oxygen	3.4	9.8	14.2	21.8
Nitrogen	1.3	1.1	.9	.6
Sulfur	1.2	.86	.66	.23
Chlorine	.05	.15	.21	.33
FUSION TEMP. °C				
Init. Def.	1274			1116
1st Soft.	1308			1151
2nd Soft.	1335			1179
Fluid	1371			1213
% Weight Rate d-RDF	0	35	52	100
% Heat Rate d-RDF	0	20	37	100

*Unless otherwise noted, all values are weight percent on a wet basis.

psi to about 149 psi and generally stayed at this level. The drop occurred because the feeders were not capable of feeding a sufficient amount of d-RDF to the boiler to maintain steam pressure. The steam flow remained approximately the same at about 30,000 pounds per hour.

Following the successful 0:1 test, a 1:1 blend was fired. During this test there was frequent clinkering on the grate. One cause of this clinkering is that when a fuel with too low an ash fusion temperature is placed on the grate and agitated, hot particles with molten edges roll against each other as the grate is vibrated. As the particles are quenched, they stick together and begin to form a slag layer across the entire surface of the grate. This slag layer becomes progressively less permeable than the open portions of the fuel and ash bed, consequently less air is supplied to the fuel/ash bed experiencing clinkering. As fuel is fed into the furnace and falls on top of the pancake, the airflow is further retarded and the clinkering condition is further aggravated. In a short time, smoking becomes severe and the fuel depth over the clinkering area on the grate increases appreciably.

The ash fusion temperature analysis of the coal revealed that the hemispheric reducing ash fusion temperature was 1477°K (2170°F). [Detroit Stoker Manufacturing Company recommends that Eastern bituminous coals should have a minimum ash fusion temperature of 2300°F (1260°C) for vibrating grate applications.] Consequently, the clinkering experienced during the coal only burns was not surprising. Since continuation of this clinkering during blend firing would not permit evaluation of the effect of pellets, procuring a different coal for subsequent tests was indicated.

Even though the pellets have an ash fusion temperature less than that of coal, the furnace operated satisfactorily when the 100 percent pellets were burned. Applying the ASME definition [Winegartner, E.C., Coal Fouling and Slagging Parameters, American Society of Mechanical Engineers, 1974.] for lignite type ash as a calcium plus magnesium oxide to iron ratio being greater than one, indicates that d-RDF will behave similar to a lignite coal. Therefore, boiler design rules for lignite rather than those for bituminous would be expected to apply when burning d-RDF.

During January, testing switched from boiler No. 2, a 60,000 lb/hr boiler with three spreaders, to boiler No. 1, a 78,500 lb/hr boiler equipped with four spreaders. During the January tests, the boiler was fired with a 1:1 blend for 4 hours and with 100 percent pellets for 2 hours. During the 1:1 firing, the overfire air and fly ash reinjection jets were adjusted to achieve the desired flame mixing and low smoke opacity. The plume was relatively clear during both the 1:1 and 0:1 blend firings. While firing with 1:1 blend, the clinkering experienced during the December tests did not occur. This improved performance occurred as a result of the coal having a hemispheric fusion temperature of about 1646°K (2471°F). The December coal fusion temperature was 1477°K (2170°F).

When the blend ratio was changed to 100 percent d-RDF, the fuel bed remained clear for the first 20 to 30 minutes of firing and there was no significant smoking. Subsequently, windrows were observed on the fuel bed in line with fly ash reinjection ports. Each of the windrows was in line with the double fly ash reinjection ports (one reinjector for the ash caught in the tube passes, the other for the first stage multiclone). The windrowing phenomenon could be corrected by spacing the fly ash reinjection ports uniformly across the back wall of the furnace instead of placing them side-by-side. The windrows moved well through the furnace as the grate vibrated and remained sufficiently porous for airflow. It was further observed that a base of burned out ash existed under the windrows. This observation is further support for the conclusion that the fly ash reinjection ports had not properly distributed the ash over the grate.

The furnace volume appeared more than adequate for combustion. The boiler, however, could only generate a maximum of 24,500 kg/hr (54,000 lbs/hr) of steam when firing 100 percent pellets. This unmodified stoker-fed, vibrating-grate boiler supported 70 percent of the nominal rating for 2 hours without changing the feeder when firing 100 percent pellets. The magnitude of this derating is the amount predicted by the volumetric limitations for the feeder. Also, the blower capacity was sufficient to meet the underfire air requirements. There was no apparent reason why the unit could not support full boiler capacity if the feeders were sized to pass the required amount of fuel on a Btu basis.

When a 1:1 blend was fired, there was no difficulty in maintaining the boiler steam pressure. However, when 100 percent pellets were introduced, the steam pressure fell to about 145 psig while carrying a 54,000 lb/hr steam demand. This drop in pressure occurred due to volumetric feeding limitations of the spreader stokers. After the initial loss in pressure, the boiler operated in a stable condition for the rest of the test.

The principal change required during the 1:1 and 0:1 blend tests was to reduce spreader rotor speed such that the throw of the pellets was approximately 6 inches less than that for 100 percent coal. This adjustment was necessary to prevent rear wall fuel impingement.

During the combustion tests with 1:1 blend and 100 percent d-RDF, the fireball was kept well away from the walls of the furnace by adjustment of the overfire air. Once these jets were adjusted for minimum smoke and maximum efficiency for coal only burning, they continued to meet the mixing and wall protection requirements when burning blends and 100 percent pellets. As viewed from the side of the furnace, firing both pellets and blends, the bed was well burned out by the time it approached the front ash pit. The flame pattern above the grate indicated that the fuel bed was maintaining proper porosity and that the combustion was good. With little attempt to optimize the system, a 10 to 12 percent carbon dioxide content in the flue gas at the boiler outlet was readily obtained.

Normal Boiler Operation

The cold and hot flow tests showed that d-RDF could be successfully introduced into the boiler. The blend also had a distribution pattern on the furnace floor which was similar to that of coal. This finding is not particularly surprising since the size distributions and material densities of the coal and pellets were similar. Therefore, with the same velocity and angle of injection into the furnace, pellets and lumps of coal with equal weight would be expected to carry approximately the same distance.

There was a severe ash accumulation on the back furnace wall in line with one spreader during the May testing. To stop the slagging, the throw of all pellets was reduced approximately 6 inches, and the circular tray in the spreader was pushed in slightly to reduce the arch of the pellet trajectories. After this adjustment, the pellets still carried the same distance from the feeder and landed at the same point on the grate. However, the 6-inch throw reduction eliminated the ash accumulation on the furnace wall, and minimized smoking. In December, January, and March, there were no problems of material impinging on the side walls. In May, however, the same spreader had to be adjusted because of its throwing too far and spraying the side wall of the furnace. Careful measurement of the spreader showed that the circular tray had worked left. Once the tray was properly aligned, the fuel impingement on the left side wall was eliminated.

During January and March, boiler No. 2 had a recurring problem of clinkering on the left side when burning coal. Reports received after the field testing stated that this clinkering had been eliminated by readjusting the spreader circular tray.

Proper adjustment of the spreader stokers is critical to the successful combustion of coal:d-RDF blends. During part of the March tests, there was a reoccurring clinkering in front of one spreader, but the rest of the fuel bed remained free-burning. Clinkers formed on top of burnt-out ash and moved out of the furnace with difficulty. The back wall of the furnace remained clear throughout the clinkering. During an unexpected furnace outage caused by a control loop failure (the d-RDF in the furnace was not related to this failure), the furnace spreaders were inspected. While the other spreaders were clear, the specific spreader had a heavy accumulation of partially pyrolized pellets in the feed throat. Careful measurement of tray position from the inside of the boiler indicated that the pellets were being thrown at too high an angle out of this spreader, ricocheting off the refractory feed throat, and accumulating at a point in the furnace approximately two-thirds of the way back. This misadjustment was solved by adjusting the circular tray. The furnace was then brought back on line from a cold start with a 1:2 blend and run continuously for 48 hours with no further clinkering.

Ash Handling

The boilers tested are equipped with dry pneumatic ash handling systems including an ash pit, cyclone separator, and storage silo. Observations regarding ash were made as to grate performance, bottom ash, ash storage silo, and reinjection ash flows.

Some relatively minor adjustments were necessary to the grate operation when firing blends in order to maintain a proper bed. As the d-RDF substitution ratio increased, the frequency and/or duration of the grate pulses were increased to maintain uniform bed depth. Pulse frequency was the main control.

As expected, the quantity of bottom ash as measured in the pit increased with d-RDF. However, the conventional pneumatic ash handling system adequately processed the coal:d-RDF ashes.

In the storage silo, some difficulty was noted with 100 percent d-RDF firing. The bottom ash was so fine that it would not de-intrain properly in the cyclone causing evential plugging of the ejector.

Observations made of the reinjection ash flow indicated that the fraction of ash falling to the ash pit was roughly independent of the type fuel being used (i.e., coal only or d-RDF). It was, however, dependent on the ash content of the blend. Further observations indicated that the combustion in these boilers was improved as d-RDF was substituted for coal. Because of this, the relative ash flow measurements for various coal:d-RDF blends are perhaps deceptive.

There was a trend toward finer ash with increasing d-RDF content.

Air and Gas Handling

The boilers tested had three air systems: underfire air, overfire air, and an induced draft fan. Observations of operating requirements for these indicated that coal:d-RDF blends can be fired in the same settings as coal only if adequate air is available to prevent clinkering during load sheds. The overfire air flow needs to be increased approximately 100 percent to compensate for the higher volatile content of the d-RDF as compared to the coal.

Fouling, Slagging, and Wastage

The coal:d-RDF blend firing resulted in occasional slagging, slight fouling, and perhaps wastage. However, the boilers were operated at low loads and high furnace temperatures were not encountered. Even under these conditions, the slagging and fouling problems were corrected with boiler adjustments. Metal wastage observations were complicated because of inadequate exposure times and methodologies available for the tests. Wastage rates observed, however, were low. This observation is encouraging especially when one considers that experiences at Ames, Iowa, have shown that after 1000 hours of in situ boiler tube exposures to RDF/coal burning, virtually no corrosion occurred. Year exposure results are apparently similar.

Energy and Mass Balances

Energy and mass balances for the tests are summarized in Tables 5 and 6. The high carbon losses in the refuse are unusual and account for the low efficiences. In reviewing the mass balance, an abnormally high amount of ash reported to the collector. Such an ash weight distribution is not normal for expected boiler performance.

Because a significant drop in carbon content of the collector ash occurred with increasing d-RDF (for 1:1 to 1:2 blends) effectively offsetting wet flue gas losses, the boiler efficiency did not appreciably change.

A positive result of the tests was the substantially improved low-load performance and decreased plume opacity when d-RDF was substituted for coal.

SUMMARY OF BOILER TESTS

The Hagerstown experience has contributed to available knowledge of blend behavior in a spreader stoker. The fuel entered the furnace satisfactorily, burned well, and met plant energy requirements. The operative and control differences encountered were all manageable, and simple adjustments usually resolved them. Some biasing of the air controls was required to prevent slagging on the fuel bed during load sheds. The only other limitations on the boiler operation occurred when the boiler was operated on 100 percent d-RDF. During this time, both the spreader and ash handling systems became capacity limited.

Proper adjustment of the spreader-stoker is critical to prevent slagging and fouling. Some slagging and fouling occurred on the walls slightly above the grates but was readily removed. The corrosion experiment produced material wastage results comparable to what one might expect for coal-only firing. This test was too short in duration, however, to permit any definite conclusions with regard to material wastage.

ENVIRONMENTAL TESTING

The emissions testing performed are indicated in Table 7. Although the quantitative results for the coal:d-RDF emissions are significant, principal conclusions are based on comparisons of coal:d-RDF blends with coal-only results. Baselines were established before and after each blend run by replicating all tests for coal-only firing conditions.

Particulate Emissions

Opacity--
Opacity decreased with increased d-RDF in the blends. Because the boiler plant tested has a significant amount of carbon carryover when coal is fired, most of the plume opacity reduction measured can be attributed to improved combustion conditions when the blends were fired.

A Battelle Tenex Sampler for trace organics was only used three times, i.e., at 1:0, 1:1, and 1:2 test blends. The Tedlar bag provided a record sample of the flue gas. When the measured emissions pro-

TABLE 5

HEAT BALANCE SUMMARY

	AS RECEIVED			
BLEND	1:0	1:1	1:2	0:1
PARAMETER				
Fraction of Rating	.17	.33	.30	.19
Excess Air (%)	104	82	99	113
LOSSES				
Dry Gas	17.9	13.7	17.8	19.4
Fuel Moisture	.1	.9	1.2	4.0
H_2O for H_2 Combustion	4.0	5.1	5.4	8.1
Combustibles in Refuse	18.3	25.3	16.6	3.0
Radiation	3.7	1.8	1.8	3.7
Unmeasured	1.5	1.5	1.5	1.5
TOTAL	45.5	48.3	44.1	39.7
EFFICIENCY	54.5	51.7	55.9	60.3

TABLE 6

ASH MASS BALANCE

Blend Coal:d-RDF	Fuel Flow Kg/hr.	% Ash in Fuel	Ash in Fuel Kg/hr.	Bottom Ash Kg/hr.		Fly Ash Kg/hr.		Collector* Kg/hr.	
				Carbon Free	With Carbon	Carbon Free	With Carbon	Carbon Free	With Carbon
1:0	872	21.9	191	82	89	5	7.7	104	219
1:1	1489	23.3	347	232	238	5	6.8	110	369
1:2	2035	23.4	476	324	341	7	10.2	145	300

*Note: 1) The collector weight was determined by difference.

TABLE 7

EMISSIONS TESTS PERFORMED ON d-RDF/COAL BLENDS COMBUSTED IN HAGERSTOWN TESTS

Test Method	Measurement
EPA Method 5	Particulate mass flux, Cl, F, SO_2, SO_3, and trace organic and inorganics.
Cascade Impactors	Particulate size distribution
EPA Method 7	Nitrous oxides
Orsat	CO_2, O_2, CO
AID Gas Chromatograph	Total hydrocarbons
Wahlco Probe	Resistivity
Tedlar Bag	Record sample
Theta Senors, Inc. Tri-gas Meter	CO_2, SO_2, NO_2 (Continuous)
Leads Northrup Transmissometer	Opacity (Continuous)
Draeger Tubes	CO, CO_2, SO_x

duced unusual results, the Tedlar bag sample was used to further clarify the data through gas chromatograph analysis.

Particle Mass Flux--
The particulate mass flux in the flue gas was reduced with increasing blend ratios, i.e., 1:1 and 1:2 blend firing until the 0:1 or 100 percent d-RDF firing was reached. The reductions, however, were not significant at the 90 percent confidence level. The data show that when 100 percent d-RDF is fired, the fuel ash increases more than offsets the fly ash carbon reductions.

Size Distribution--
The size distribution was shown to shift toward fines as d-RDF was substituted for coal. Two reasons for this are the improved burnout of the aerosol (producing smaller particulates) and the large number of fine paper platelets in the d-RDF causing the number of particles formed to increase.

Fly Ash Resistivity--
Table 8 summarizes the effects of substituting d-RDF for coal on aerosol resistivity. The 1:1 blend fly ash has resistivities around 10^{10} ohm-cm, within the range of 10^8 to 10^{10} ohm-cm required for efficient precipitator performance.

TABLE 8

EFFECT OF SUBSTITUTING d-RDF FOR COAL ON AEROSOL RESISTIVITY

	Resistivity (Ω-cm)	
Blend	March Tests	May Tests
1:0	$<10^7$	$6x10^7$
1:1	$8x10^9$	$2x10^{10}$
1:2	-	$1x10^{12}$
0:1	-	$1x10^{12}$

Gaseous Emissions

During the Hagerstown tests, data were collected on emissions of SO_2/SO_3, total oxides of nitrogen, halogens, hydrocarbons, trace organic, and heavy metals. Results are summarized below:

SO_x--
For 1:2 and 0:1 blend firing, there was a small, but significant reduction in overall SO_2 emissions with the replacement of higher sulfur coal by 0.6 percent sulfur d-RDF. For 1:1 blends, the sulfur reduction was too little to be distinguished, but as one would expect, reductions in sulfur emissions appear to be porportional to the reduction of sulfur in the fuel burned.

NO_x--
An evaluation of NO_x emissions data revealed that NO_x emissions did not change significantly when d-RDF was substituted for coal.

Halogens--
Analyses of data on chlorine and fluorine emissions indicate that a significant

increase (factor of 16) occurred when d-RDF is substituted for coal.

Although the chlorine levels in d-RDF are about the same as some coals burned in the United States and Europe, the coal:d-RDF blends emit more chlorine per unit of energy than most coals because of their lower heat content.

Hydrocarbons--

The hydrocarbon emissions from the d-RDF-coal blends did not differ significantly from those for coal only.

Trace Compound Emissions

The flue gases were evaluated for polycyclic organic compounds and heavy metal emissions. Based upon the test results, the overall emissions of polycyclic organic compounds for blend firing and coal only were below the threshold limits being proposed by the National Academy of Science.

The actual amounts of various trace inorganic elements found for all blends were generally considered not abnormal. Some trends were observed. There as a tendency for Br, Mn, Pb, and Sb to increase in concentration with increasing coal:d-RDF ratios indicating that the refuse is a contributor of these elements. As, Ni, and Vn decreased with increasing RDF.

SUMMARY

Tests conducted thus far have been encouraging, especially from the standpoint of operations in the boiler facilities. Boiler performance has been generally acceptable while burning blends of d-RDF and coal; environmental effects appear acceptable, and handling of d-RDF can be accomplished satisfactorily.

Perhaps most discouraging at this time has been the problem of achieving acceptable production rates for d-RDF using the CPM. Since throughput capacities of the densifier will greatly effect economics, this is an important consideration. We are hopeful that the production experience gained at NCRR and those to be gained at Teledyne will help to ease this situation. Work using different densification equipment is also required.

Also important to the economics will be the final characteristics required for an acceptable d-RDF. As more processing is required, costs will be increased. However, perhaps the d-RDF does not have to be a well formed pellet (or other shape) and can contain relatively large amounts of fines. This would help to increase densifier production. The additional testing planned will help to determine if this is the case.

Storage of the d-RDF during this project, although unusual, has indicated the d-RDF can be stored for at least a one month period. Storage recommendations were provided. Handling was also routinely done. Additional work would be useful, however, to demonstrate that blends of d-RDF and coal can be routinely handled over extended periods in existing boiler equipment.

Currently the d-RDF program is implementing a second phase of combustion tests at the General Electric Plant in Erie, Pennsylvania. We plan to burn approximately 2,800 tons of d-RDF produced by NCRR and Teledyne. A full battery of tests will be done to further characterize the effects of using d-RDF in existing stoker boilers. Hopefully, results of these tests will demonstrate that d-RDF can be successfuly used in existing smaller institutional, industrial, and utility power generating facilities.

ACKNOWLEDGEMENT

Work reported here is primarily a summary of activities conducted by NCRR under Research Grant R804150 "Preparation, Use and Cost of d-RDF as a Supplementary Fuel in Stoker Boilers," and by Systems Technology Corporation under Contract 68-03-2426 "Effects of Burning Densified Forms of Municipal Solid Waste Derived Fuels in Industrial, Utility, and Institutional Stoker Boilers." Dr. Harvey Alter and Jay Campbell of NCRR and Jerry Degler of Systems Technology provided major input to this paper. Work has also been done in cooperation with the Industrial Environmental Research Laboratory, Cincinnati. All wish to thank the State of Maryland personnel for their interest and cooperation.

STATUS, TRENDS, AND IMPEDIMENTS TO DISCARDED TIRE COLLECTION AND RESOURCE RECOVERY

James F. Hudson
Patricia L. Deese
Douglas Funkhouser
Urban Systems Research & Engineering, Inc.
36 Boylston Street
Cambridge, Massachusetts 02138

ABSTRACT

As part of its legislative mandate under the Resource Conservation and Recovery Act, EPA is required to study the problems associated with scrap tire reuse and disposal. USR&E is under contract to perform a technical, environmental, and economic assessment of the various reuse and disposal options, and the use of economic and regulatory approaches to assure the most efficient use of limited resources.

While the project is in its early stages, it is possible in this paper to describe most of the available options, and the market structure factors which make them more or less attractive. The technical options include retreading, increases in tire lifetime, baling or shredding for improved landfill disposal, material for artificial reefs, use of ground tires as an additive to coal for fossil fuel power plants, rubber reclaiming, use of ground tires in pavement and road construction, and a host of minor uses, plus processes in the development stages. Key impact points for regulations or pricing mechanisms are also identified.

INTRODUCTION

Section 8002h of the Resource Conservation and Recovery Act calls for EPA to prepare a report to Congress on "discarded motor vehicle tires which shall include an analysis of the problems involved in the collection, recovery of resources including energy, and use of such tires."[1] As the basis of that report, the Office of Research and Development has contracted for a study of the waste tire problem, and this paper presents some preliminary information from that study which began in September 1978 and is scheduled to be completed in September 1979. The paper is divided into two major sections: the first describes the flow of passenger car tires, based on 1976 data, and identifies the potential impact points for economic and regulatory actions; the second describes the technologies for reuse and disposal, based on data from the literature. As the project progresses, the information contained throughout will be updated, and it will become possible to make recommendations for EPA and Congressional action.

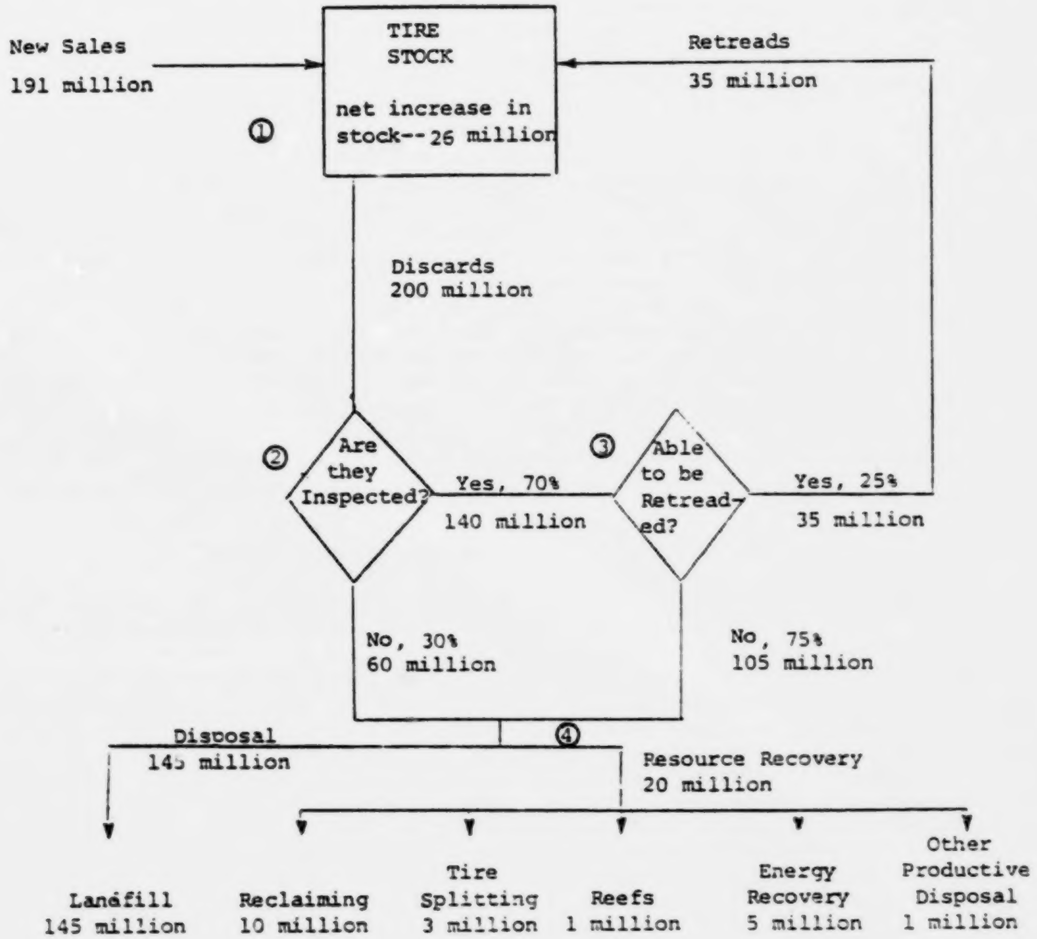
ENVIRONMENTAL IMPACTS, AND MATERIALS FLOWS AND POINTS FOR POLICY IMPACT

Each year over 200 million tires are produced to be used as original equipment on new vehicles, or to replace worn out tires. Eventually, the tires can no longer be used for transportation purposes and must be disposed of. The most common method of disposal provides landfilling without size reduction. As much as 90% of all tires are currently landfilled, once their useful life is over. This creates an environmental problem, and represents a fairly large loss of resources. Although scrap tires account for no more than 1.5% of the total solid waste stream, they can cause significant environmental damage.

Tires landfilled in large numbers tend to rise to the surface, creating aesthetic insult and reducing land reuse; they also provide a breeding space for rats and disease vectors, causing a public health

FIGURE 1

APPROXIMATE 1976 PASSENGER TIRE BALANCE


New Sales
191 million
TIRE STOCK
net increase in stock--26 million
Retreads
35 million
①
Discards
200 million
②
Are they Inspected?
Yes, 70%
140 million
③
Able to be Retreaded?
Yes, 25%
35 million
No, 30%
60 million
No, 75%
105 million
Disposal
145 million
④
Resource Recovery
20 million
Landfill
145 million
Reclaiming
10 million
Tire Splitting
3 million
Reefs
1 million
Energy Recovery
5 million
Other Productive Disposal
1 million

○ Impact points for policy analysis

hazard. On the other hand, if they are shredded or sliced, they compact better and prevent aesthetic and public health damage. The reason tires are not shredded prior to landfill may be explained in terms of external costs, since the environmental consequences of dumping are borne by the general public, and the individuals who dispose tires have no incentive to pay the additional costs of shredding and slicing. These costs have been estimated at $.50 to $2.00 per tire.[2]

The energy requirements for the average passenger car tire have been estimated at seven gallons of oil or its equivalent--including both material and process energy.[3] While not all of this can be recovered, the use of waste tires for energy production is becoming increasingly common.

Because of the market's failure to realize the socially optimal tire management and disposal practices, government has a legitimate role in attempting to reduce the number of tires discarded, and to promote environmentally-sound disposal techniques. This paper is concerned with the role of the government in this area, in particular with potential government action. The existing tire management and disposal systems in the private sector and the federal government must be analyzed to accomplish this.

Figure 1 shows the system components, along with USR&E's estimates of passenger tire flows for 1976. The impact points where Federal policies could affect the system are shown in the figure. Point 1 is the tire stock and total sales, where increases in the lifetimes of either new tires or retreads could, potentially, reduce the resources used in tire production. This could be accomplished by improved maintenance practices, or improved tire design.

Impact point 2 is inspection for retreading after discard. Since retreading results in the most benefit of any approach available at present, increased inspection would probably lead to net benefits which would be desirable. Tire deposits refunded to those who turned in old tires would be one mechanism that might be useful.

Point 3 is related to the results of the inspection. Standardization of tires, or improvements in quality control potentially lead to an advanced retread technology and market, which could be induced by federal incentives. Increased carcass quality or economic benefits for retreading are examples of federal incentives.

At Point 4, the disposal decision, the costs and availability of various disposal options will be crucial. Increased landfilling costs, and increased availability of other disposal methods, will result in increased resource recovery. Federal actions are possible on all sides of this system, ranging from economic approaches such as product charges
of technologies or enforcement of landfill standards.

Before recommending specific options for each of these impact points, it will be necessary to improve the data on current materials flows, and analyze the costs, technical feasibility, and environmental impacts of the various disposal options. This work is currently underway.

METHODS FOR RESOURCE RECOVERY, AND FOR REDUCING ENVIRONMENTAL IMPACTS

Extending Tire Lives

Shorter tire lives increase the volume of tire production, and result in increasing tire disposal volume. Therefore, extending tire life may be viewed as the first step in tire management. Assuming that roughly 10% of the scrap tires find "productive" (non-landfill) final uses, approximately 2.5 million tons of scrap tires would be landfilled each year. This corresponds to roughly 1.5% of the total solid waste stream. However, as discussed above, scrap tires present a particularly difficult disposal problem, and also represent a loss of resources.

Tire consumption--or rather tire mile consumption--may remain constant, or even increase with no corresponding increase in tire production, if the useful life of tires is extended. Reducing the need for tire production also reduces resource consumption, as well as the volume of tires --entering the waste stream.

Procurement of longer life tires, proper tire maintenance and retreading are the three major means for extending tire lives. Each of these will be discussed in turn.

Procurement

The purchase of longer life tires reduces the number of tires consumed, produced and eventually disposed of. Currently radial tires achieve the highest mileages, and have the longest useful lives. Most sources estimate 40,000 miles for radials, and 20-25,000 miles for bias and bias belted tires. However, radials in GSA motor pools in 1975 obtained 24-26,000 miles, while bias and bias belted tires averaged 15-25,000 miles. Actual mileages obtained depend on a large variety of factors--including driving habits, road composition, and tire maintenance.

According to some sources, the manufacture of radials has higher resource and energy requirements than bias and bias belted tires, but no actual figures have been obtained for comparative purposes. If the mileage gain outstrips the increases in resource requirements, radials may be expected to reduce the size of the scrap tire problem. In addition, radials improve gas mileage by 5-10%, further reducing energy requirements and air pollution from mobile sources.

Radials also represent some marginal economic benefits for the consumer--slightly lower tire costs per mile travelled, improved gasoline mileage, elimination of the time costs of purchasing replacement tires, as well as the out-of-pocket-costs of replacing the tires. The market share of radial tires has been increasing in replacement use from 23% in 1974 to 36% in 1976. According to another estimate, radials are now 67% of original equipment tires and 35% of replacement tires--accounting for an overall market share of 44%. They are particularly important for passenger vehicles, while trucks and farm equipment still utilize bias and bias belted tires for the most part. The soft sidewalls and radial belts of radial tires are not suitable for farm requirements, but are desirable for highway trucking largely because of lower heat gains in travel.

The manufacture and procurement of the 100,000-mile tire would extend tire lives beyond those of the radial tires. Technologically it is now feasible to manufacture 100,000-mile tires for passenger vehicles, but product quality and economics make its use doubtful, despite favorable studies of the tire by some analysts.[4]

Tire Maintenance

The second major method of extending tire life involves proper tire care and maintenance. Correct inflation, wheel alignment, prompt repair to small damages, and frequent inspections are some of the components of tire care. Tire care and maintenance extends the original life of the tire, and enhances its retreadability by maintaining the casing in good condition. Properly maintained retreads also obtain higher mileage than those not cared for.

Retreading

Retreading is the third major method for extending the useful lives of tires. According to an article in the Retreader's Journal,[5] the number of passenger tires retreaded was 30.5 million in 1972, 35.3 million in 1975, and was expected to be 35.5 million in 1976.

Passenger tires are normally retreaded only once, while truck tires average 3 to 5 retreads. Airplane tires, on the other hand, may sometimes be retreaded up to 22 to 23 times,[6] and routinely average 7 or 8. The reason for the variation is the relative loads and levels of care in the three tire types.

The market share of the retreads has been decreasing, primarily because of supply constraints. Retreaders could sell all the retreads they wanted, but do not apparently have a sufficient supply of suitable casings.[7] The proportion of inspected tires actually accepted for retreading varies a great deal depending on the quality of the carcasses inspected, as well as on the standards of the retreading operation.[8] Increasing tire collection and inspection rate would augment the supply of casings, but improved maintenance is also required before significant gains can be made. Radials have been prone to belt-edge separation, reducing their suitability for retreading. The supply constraint in this area is particularly significant, but improved radial designs and retread techniques should reduce the number of discards.

Retreading decreases tire consumption without affecting mobility. It represents environmental benefits through reducing the volume of the solid waste stream, resource savings through lowering the energy and materials requirements per tire mile, and substantial savings to the consumer in terms of expenditures for new and replacement tires. The average passenger tire retread requires 8.7 pounds of (retread) rubber, while a new tire requires about 22 pounds of rubber (not including process waste).[9] If mileage is doubled through retreading, solid waste generation is reduced by 13 pounds. Retread quality control may be a key issue.

Even with the procurement of longer life tires, proper tire maintenance and retreading, tires eventually wear out, and can no longer be used for transportation. Proper resource recovery and disposal techniques must then be selected to reduce resource loss and environmental damage.

Resource Recovery - Whole Tire Methods

Breakwaters: Scrap tire breakwaters represent an increasingly attractive use of waste tires.[10] Mats of tires, one-half wavelength wide, can reduce wave heights from 4' to 1', and are useful in waves up to 5'. In one case, a Rhode Island yacht club built a breakwater 500' x 21' for $2,500 plus donated labor. These costs appear typical. Because of the energy-absorbing ability of tires, the breakwaters require little maintenance and will continue to be effective for long periods. The potential for this use is unknown; however, it should probably remain in the private sector with the users paying the costs.

Artificial Reefs: Certain species of fish prefer rocky, partially enclosed habitats for protection and shelter. Since many of these fish are sport or commercial species, the development of artificial reefs can be of benefit to anglers and the public. Tires have been used for artificial reefs because they are inexpensive, inert, and seem to offer desirable habitat.

Several configurations of scrap tires have been used for artificial reefs, with various costs depending on the labor and materials required to construct and move the modules.[11] Installation costs for the simplest methods have been estimated at 30¢-40¢/tire, plus tire acquisition costs.[12] Goodyear estimates present use at 500,000 tire per year, but the potential for use of up to one billion tires has been claimed. Since one reef in Florida is expecting to use 500,000 per year, much higher levels can be expected.[13] The cost can often be recovered from private angling groups or sport fishing associations, as contributions of money or labor.

Artificial reefs are less prevalent on the West Coast, partially because of more difficult conditions; fresh water uses (particularly in artificial reservoirs) are just beginning.

Crash Barriers and Abutments: Rubber tires in carefully designed configurations can be used to considerably reduce crash impact damage. At present, Goodyear estimates that about 200 million tires (or one year's disposal) could be used for such abutments in well-identified points. This is an area which EPA could coordinate with NHTSA and FHWA, since it would involve highway applications for safety improvements. Cost estimates are necessary.

Heat Recovery: One energy recovery experiment incinerates tires heat recovery. This system uses a cyclone furnace and accepts whole tires with a capacity of about 36 tons per day. This would lead to an estimate of about 3 million tires/year (another estimate in a Goodyear press release is 1 million tires/year). This would generate 25,000 pounds of steam per hour at 250 psi.[14] The economics analysis of this plant is still underway, but appears unfavorable at present.

Resource Recovery - Shredded or Split Tire Methods

Use of Tires as Road Materials: Tires appear to provide an attractive additive for road-building, when properly prepared. Several options have been suggested, all using tires which have been shredded or ground to the correct size, after metals and textiles have been removed. Devulcanization may also be an aid in some instances, indicating a potential market for the reclaimation industry. At present, reclaim and retread buffings are products which have consistent particle sizes and purity.

Joint sealing, another use for waste rubber, is performed on the New York Thruway.[15] The flexibility of the rubber adds life to the joints, reducing necessary maintenance and ultimately saving on materials. Thus, the process has net benefits for New York even though initial materials costs rise. Goddard estimates that the use of scrap rubber would be advantageous at any rubber price up to 29¢/pound,[16] which is at current prices.

The use of rubber in seal coats is another option. These are placed over existing streets to cover cracking. The rubber (mixed in at up to 35%) extends the life of the seal coat considerably by providing elasticity to reduce cracking from temperature and load changes, and also reduces the speed with which cracks in the underlayers propogate to the surface. This has been demonstrated in Phoenix and other areas by McDonald.[17] Goddard estimates its value at 60-70¢/pound of rubber used, though this may be an overestimate.

Rubber has also been suggested as a constituent in bituminous concrete 6% bituminous concrete could potentially contain 1% to 2% waste rubber.[18] If this proved advantageous, most of the presently discarded scrap tires could be used in this manner, and the straight asphalt mix could use the remainder. However, few engineering benefits have been shown for this product.

Other options including using rubber and asphalt or coal tar in an emulsion as a road dressing for driveways, parking lots, or streets. Skid resistance is improved, weathering may also be aided, but no cost data are available. Goodyear claims to have

> used ground-up tire mixed with an adhesive to produce a resilient artificial turf. This springy surfacing material may be tinted a variety of colors for use on playgrounds...the economics of production are not favorable, but the process is under further consideration.[19]

One of the most attractive uses is for a "strain relieving interlayer" between a new road surface and the underlying layers. The flexibility and elasticity of the rubber reduces cracking and stresses on the upper layer. Experiments are underway nationally which employ this use.

Two independent federal studies have suggested these various asphalt uses as suitable methods for federal tire disposal, and deserving of federal promotion. Of the alternatives studied, Goddard found the asphalt uses the most economically attractive, even at present prices of 10¢-12¢/pound. Hedley, et al suggested cryogenic grinding (see below) which shows recovery as an asphalt additive as one of the most attractive uses for military waste tires which can no longer be retreaded.[20] One estimate suggests material cost increases for rubber additives as

- 4.5% for using powdered rubber additive in resurfacing;
- 5.5% for a rubberized binder in resurfacing;
- 28.5% for using a rubberized binder in chip sealing; and
- 14.8% for adding a strain-relieving interlayer.[21]

The asphalt industry produces about 5.4 million tons yearly, which has a potential recovery of over 100 million waste tires at 25% use with the asphalt.

Embankments: Tire uses in embankments and retaining walls were mentioned by one source, and appear attractive. At this point, we have only limited information on them, and have no data on their potential use of tires or economic analysis. It appears that halved tires can provide sufficient structural support for embankments which are almost vertical, when bolted together correctly. Embankments are constructed of alternating layers of tires and earth.

Oil Spills: The use of shredded waste tires, along with polystyrene scrap, for absorbing spilled oil was described in one source. The materials have good capacity for absorbing the oil, can be collected easily, and can supposedly be converted through heating into a form similar to asphalt for reuse.[22]

Tire Splitting: This industry is not expected to be a major growth sector. The plants are relatively low-polluting, selling approximately 35% of their input as new products, and selling pieces to reclaimers (as of 1968). Their input in 1968 consisted of about 60 million pounds, or about 2.4 million passenger tire equivalents. Thus, they are likely to continue to be tire users, but their limited market will keep them fairly small, accounting for under 2% of the waste tires for the near future. Note that these data are several years old, and deserve updating if EPA plans any major effort in the area.

Tire Derived Fuel: General Motors has experimented with the use of shredded tires as supplementary fuel in a power plant burner.[23] The tire chips were purchased from a tire outlet company, stored in an old farm silo, and added to the coal on a conveyor belt in the ratio of 1 to 9. During the experiment, shredded tires were obtained at a cost of $24/ton, which may be compared with the price of coal--at that time--of $40 per ton. For a continuing supply of shredded tires, however, the quotes averaged $40/ton, while coal prices sagged to around $30/ton. The use of tire chips required additional handling and environmental controls, both increasing the costs of tire chips relative to coal. One of the difficulties in the GM experiment was that the furnace was not designed for handling large chunks of materials--the requirements for fine particle size implied high shredding costs. Furnaces designed to handle larger pieces may be able to obtain shredded tires at substantially lower costs--at approximately $20 per ton, and with high BTU value.

Reclaimed Rubber: Probably the best description of the reclaimed rubber industry's present performance is that in the U.S. Industrial Outlook[24] which states:

> An unfavorable cost/price structure, some old inefficient plants, and significant environmental problems have continued to plague the reclaimed rubber industry...industry shipments have declined 50% since the late 1960's. The use of reclaim in radial tires has been less than in bias-ply tires.

The reclamation industry received about 576 million pounds of rubber in 1968, of which something like 85% was post-consumer waste, largely from tires.[25] The Commerce estimate was extrapolated to a present use of about 300 million pounds, which would mean disposal of about 10 million passenger-tire equivalents. Of this, about 2 million came in as waste from the tire-splitting industry. In other words, reclamation is important, but its impact is not particularly large at present.

One of the major potential uses for reclamation products is in asphalt additive. The cleaned, ground rubber is the major source for small high-quality additive, with tire buffings from retreaders representing another major source.[26] However, cryogenic grinding may tend to undercut this market so that the reclamation industry will continue to have difficulties selling its product profitably.

Advanced Chemical Methods: There are a number of advanced systems for tire recovery which generally involve breaking down the tire into its components. These, in turn, can be used as fuels and process feedstocks. The most advanced of these is probably the Goodyear/TOSCO pilot plant in Rocky Flats, Colorado, which uses "oil shale recovery technology" to convert the tires into oil, carbon black, and steel. They claim that a full-scale plant would process 8 million tires/year, providing 15 million gallons of oil, 73 million pounds of carbon black, and 2 million pounds of scrap steel (for steel-belted tires). This would be sufficient for the production of 2 million new tires, if all worked well.[27]

Other processes under a number of names have been developed, each with unique characteristics.[28] For example, the destructive distillation process developed by Firestone and the Bureau of Mines would convert tires into char, oil, and gas for use as fuels or feedstock. Hydrogenation has also been suggested, as have depolymerization, pyrolysis in salts, etc. The similarities and differences of these processes are not important to EPA at this time, unless demonstration grants are contemplated. They are, at best, several years away from full-scale implementation, and few cost estimates of any kind are available. The technologies are available in R & D, but there is no strong evidence concerning their economics or practical implementation.

Sanitary Landfill Disposal

The sanitary landfill is the last resort for waste tires, as for most other solid wastes. In most cases, these will be commercial landfills receiving wastes from industries--particularly tire dealers, retreaders, and auto scrappers--although some tires do enter the municipal waste stream.

Landfilling tires is a difficult process, since they do not compact well, tend to migrate to the surface, and form an attractive breeding ground for disease vectors.[29] Thus, size reduction or baling of tires would be desirable as landfill practice. Landfill receives the bulk of waste tires at present.

Size Reduction

Size reduction is required for most high-value applications of the waste rubber, and is the first step in the rubber reclaiming industry. Some size reduction is required for landfill, to allow easy disposal and reduce the potential for environmental damage. Recent experiments have suggested cryogenic grinding for both inplant rubber waste and for scrap tires, with evidence that the sizes can be reduced to useful levels at low costs.[30] Though some conventional shredders also appear to work well, tire shredders and shears range in cost from a few thousand dollars for some portable units up to about $100,000.

FOOTNOTES

[1] Resource Conservation and Recovery Act, P.L. 94-580.

[2] J.F. Hudson and E.E. Lake. A Decision Paper of EPA Guidelines for Tire Reuse and Disposal. Cambridge: Urban Systems Research & Engineering, for the EPA's Office of Solid Waste Management Programs, December 1976.

[3] J.A. Beckman, et al. "Scrap Tire Disposal Procedures". Rubber Chemistry and Technology. 47(3):597-624; and G. Crane et al. "Scrap Tire Disposal Procedures". Rubber Chemistry and Technology. 51:577-599, 1978.

[4] R.R. Westerman. Tires: Decreasing Solid Wastes and Manufacturing Throughput. EPA-600/5-78-009, July 1978.

[5] E.J. Wagner. "Retreadonomics". Retreader's Journal, 20(5): 3-9, May 1976.

[6] Smithers Scientific Services, Inc. A Study of the Feasibility of Requiring the Federal Government to Use Retread Tires. Prepared for EPA-OSWMP, 1974.

[7] Wagner, op.cit.

[8] Tire Retreading Institute. Retreading Radial Passenger Tires. Washington, D.C.:TRI April 1976. (1343 L Street, Washington, D.C. 20005--$2.50); C.C. Humpstone, et al. Tire Recycling and Reuse Alternatives. IRT for EPA, 1974

[9] Wagner, op.cit.

[10] N.W. Ross. Floating Breakwaters. University of Rhode Island, Narragansett, Rhode Island, 1977.

[11] R.B. Stone, et al. Scrap Tires as Artificial Reefs. Report SW-119, USEPA, 1974.

[12] L. Colugna and R. Stone (eds.). Proceedings of an International Conference on Artificial Reefs. NOAA-7502009. March 1974; and Stone et al, op.cit.

[13] Colugna and Stone, op.cit.

[14] E.R. Moats. "Goodyear Tire-Fired Boiler", Resource Recovery and Conservation 1(1976) 315; and J.B. Stirbling. "Cyclone Furnaces", Engineering. October 1972.

[15] T.M. Cleary and W.H. Clark, III. "Old Tires Contribute to Thruway Maintenance", Public Works Magazine. July 1973.

[16] H.C. Goddard. *An Economic Evaluation of Technical Systems for Scrap Tire Recycling*. EPA 600/5-75-019, December 1975.

[17] C.H. McDonald. "An Elastomer Solution for 'Alligator' Pattern, or Fatigue, Cracking in Asphalt Pavements" presented to the International Symposium on the Use of Rubber in Asphalt Pavements. May 1971.

[18] J.E. Stephens and S.A. Mokrzewski. "The Effect of Reclaimed Rubber on Bituminous Paving Mixture." Civil Engineering Department, University of Connecticut. Report CE74-75. March 1974.

[19] Rubber Manufacturers Association (RMA). Packet of press releases and articles, December 3, 1976.

[20] W.H. Hedley, *et al*. *Disposal Study: Tires and Other Polymeric Materials*. Monsanto Research Corporation for Army Natick Development Center, April, 1975. Contract DAAK03-74-C-0136.

[21] B.D. LaGrone and B.J. Huff. "Use of Waste Rubber in Asphalt Paving." Presented at the Colorado State University Asphalt Paving Seminar, December 1973. (authors from U.S. Rubber Reclaiming Company).

[22] Beckman, *et al*. op.cit.

[23] R.H. Taggart, Jr. "Shredded Tires as an Auxiliary Fuel." Environmental Activities Staff, General Motors Technical Center, 1975.

[24] U.S. Department of Commerce. *1976 U.S. Industrial Outlook*. U.S. GPO, Washington, D.C., 1976.

[25] R.J. Pettigrew, *et al*. *Rubber Reuse and Solid Waste Management*, EPA, 1971 (SW-22c).

[26] Lagrone and Huff, op. cit.

[27] RMA, op.cit.; "Goodyear-TOSCO Rubber Recycling Plant." *Journal of Commerce*, p. 26, 12/24/75.

[28] Beckman, op.cit.

[29] Office of Solid Waste Management Programs. *Decision-Makers Guide in Solid Waste Management*. EPA, 1976, SW-500.

[30] N.R. Broton. "Cryogenic Recycling of Solid Waste." *Public Works* 107(9): 84-85. September, 1976; N.B. Frable. "Cryogenic Grinding Saves $$, Recycled Scrap Becomes Valuable Resource." *Rubber World*. October, 1976. pp. 66, 68, and 87; "Cryogenic Process for Recycled Tires." *Journal of Commerce*, p. 5, 9/7/77; and M.D. Kazarnowicz, *et al*. *Cryogenic Scrap Tire Processing*. Allentown, Pennsylvania: Air Products and Chemicals, Inc. (paper presented at 112th meeting of the American Chemical Society, October 4-7, 1977).

ADVANCED THERMAL & CHEMICAL CONCEPTS FOR IMPROVED MSW DERIVED PRODUCTS

N. L. Hecht & D. S. Duvall
University of Dayton Research Institute
300 College Park
Dayton, Ohio 45469

ABSTRACT

A number of resource recovery projects have been instituted to recover fuel, energy, and mineral components from refuse. Although a number of these programs have been effective, the quality of the products recovered could be enhanced to improve their marketability. The purpose of this study was to investigate the potential of known processes that could improve the quality of the fuels or other products derived from the organic fraction in refuse.

This study concentrated on those processes designed to produce a carbon char and a powdered fuel from the municipal solid waste. Of particular interest in the production of carbon char, were those chemical treatments that promote char formation at lower pyrolysis temperatures. For the production of powdered fuels, the chemical and thermal treatments which cause cellulose embrittlement were of most interest.

A major accomplishment of this project was the identification and laboratory verification of chemical treatments for cellulose embrittlement. As a result of these studies, the basic requirements were defined for producing a fine powdered fuel from the organic fraction of MSW.

Information obtained from these studies provided the basis for a preliminary engineering and economic analysis of a full scale facility to produce a fine powdered fuel.

INTRODUCTION

Due to the many problems associated with the conventional practices of landfilling and incineration, a number of new techniques are being developed to improve the management of municipal refuse. The majority of these new techniques are concerned with recovering and utilizing the valuable materials in solid waste. Resource recovery is the term applied to the numerous processes and systems being designed to recover components of waste and convert them to useful products. Systems have been developed for energy recovery; compost production; fiber, glass and metal recovery; and alcohol and protein production. The major emphasis has been on those processes designed to recover the thermal energy in waste. Although many of the systems developed have been relatively successful, the quality and consistency of the fuel produced or the energy generated has not been completely satisfactory. Higher quality and greater consistency in the waste-derived fuel or energy is necessary if it is to be marketable for large-scale usage.

The purpose of the studies conducted at the University of Dayton Research Institute (UDRI) was to investigate the potential of known processes that could improve the quality of the fuels and other products derived from the organic fraction in refuse. Since cellulose products are the major constituents of the organic fraction in refuse, it seemed likely that a number of the processes employed in the pulp, paper, and textile industries would have considerable potential for refuse processing.

This study was initiated with a comprehensive review of processes for making refuse a better fuel. Information was obtained from the open literature, and through personal contacts. Possible processes for improving the quality of products from the organic fraction derived from municipal solid waste (MSW) were determined, and descriptions were developed for each process. To better evaluate the different processes, an analytical framework for technical and economic assessment was developed to serve as a guide for analysis, as well as for the information acquisition phase of the study. The literature search identified major thermal and chemical processes used in the pulp and paper, wood, textile, and resource recovery industries.

The study, which followed, concentrated on those processes designed to produce a carbon char, and a powdered fuel from the municipal solid waste. Of particular interest for the production of carbon char were those chemical treatments that promote char formation at lower pyrolysis temperatures. For the production of powdered fuels, the chemical and thermal treatments which cause cellulose embrittlement were of most interest.

CARBONIZATION OF CELLULOSE

Thermal decomposition of refuse in the absence or partial absence of oxygen (pyrolysis) has been used for the production of useful fuels. Solid, liquid, or gaseous fuels can be obtained by a variety of pyrolysis processes. The quantity of char, bitumen-like liquid, and gas produced varies and is a function of the time-temperature sequence for each particular process. Commercial pilot and laboratory processes that utilize a variety of furnace designs have been developed to produce a wide range of fuel products. Rotary kilns, vertical and horizontal shaft furnaces, fluidized bed furnaces, and a variety of batch type reactors have been employed for fuel production. A number of these systems may reach commercial status within the next several years.

As indicated, organic liquids, char, water, and a gas are produced from the pyrolysis of cellulose. The quantities generated are controlled by the heating rate, final temperature and length of exposure to final temperature. In general, the char will constitute between 20-40% of the final product mix, the organic liquids and gas phase can vary between 10-40%, and water constitutes the remaining fraction. The thermal process employed can be designed to maximize the end products desired from the cellulose wastes. Higher heating rates and higher temperature produce larger quantities of gas and less char. Conversely, lower heating rates and lower temperature processes result in increased char production.

The quantity of char, the composition of the gases and liquids evolved, and the necessary reaction temperatures can be significantly affected by the presence of chemical agents in the cellulose materials. A number of chemical compositions have been identified which increase the quantity of char produced and decrease the amount of combustible gases and tars formed. Many of these compounds were developed for flameproofing cellulosic materials. The flameproofing agents direct the pyrolysis process toward maximum production of char, minimum production of tars, and the highest possible proportions of water and carbon dioxide. The highly effective compositions are all soluble in water, and most are salts of either strong acids or bases. In addition, many oxidizing agents attack cellulose and have been found to be effective fire retardants. Oxidized cellulose pyrolyzes rapidly at lower temperature giving high charcoal residues.

Although a number of pyrolysis processes have been developed to produce carbon char, the literature search found only one process using chemical treatment to promote char formation. In the patented process developed by Dr. A. Harendza-Harinxma, sodium aluminate ($Na_2Al_2O_4$) is used to promote carbon formation at temperatures below 660°F, whereas in most of the conventional pyrolysis processes reported in the literature, pyrolysis is achieved with thermal treatments from 930°F to 1650°F. In addition, the char yield is reportedly increased for the sodium aluminate process(1).

In Dr. Harendza-Harinxma's process, municipal refuse and sewage sludge are pyrolyzed to a char and fuel gas. In this process, sewage sludge is used as the solvent for a 2-4% solution of sodium aluminate. This solution is mixed with municipal refuse (two parts sludge to one part refuse). The slurry mixture is then mechanically dewatered, resulting in a thickened sludge which is thermally dried to about 15% moisture content. The dried refuse-sludge mixture, impregnated with sodium aluminate, is then carbonized for about one hour at 480-570°F.

Engineering Design

A preliminary engineering study of a plant to produce carbon char from MSW and sewage sludge was conducted. Based on the information accumulated, a design for a low temperature pyrolysis facility was developed. The proposed facility would process 1000 tons per 20 hour day (50 TPH) for six days per week. The basic design for this plant is based on the Black-Clawson wet processing system at Franklin, Ohio(2). The process flow essentially follows the Black-Clawson process to dewatering at the hydrodenser. After partial dewatering at the hydrodenser, the slurried refuse would be mixed with sodium aluminate and sewage sludge in a flash mixer. This slurry mixture is then mechanically dewatered in a cone press and dried in a rotary carbonization kiln. A flow plan and material balance for the proposed plant is presented in Figure 1, and an energy balance is presented in Table 1.

A plant processing 1000 tons of refuse per day could generate up to 300 tons of char per day or about 79,500 tons per year.

Economic Analysis

A preliminary economic analysis was prepared for the proposed pyrolysis plant. This analysis is based on the process flow plan shown in Figure 1. The proposed plant would have two processing lines each with a capacity of 25 tons per hour. It is assumed that the facility would be processing 265,200 tons of refuse annually [1000 x 6 x 52 x 0.85 (on-line availability)]. It is further assumed that an adjacent landfill would serve as a backup to the pyrolysis facility. Revenues for the facility would be provided from several sources: a) a tipping fee, b) sludge disposal, c) sale of aluminum and iron, and d) sale of carbon char. A summary of the calculations developed for the capital and operating costs are presented in Tables 2 and 3 respectively. Consideration of possible revenues are presented in Table 4. The data presented in these tables show an estimated total operating cost of $26.68/throughput ton of MSW and a potential revenue of $17.15/throughput ton of MSW plus revenue from sale of carbon char. For the pyrolysis facility to break even, the carbon char would have to sell for $0.017 per pound ($34/ton) in order to cover the $9.53 deficit calculated between total operating cost and identified potential revenues.

Market Assessment

A major concern is the market potential for the char residue. If large quantities are to be produced, then long term valid markets must be available.

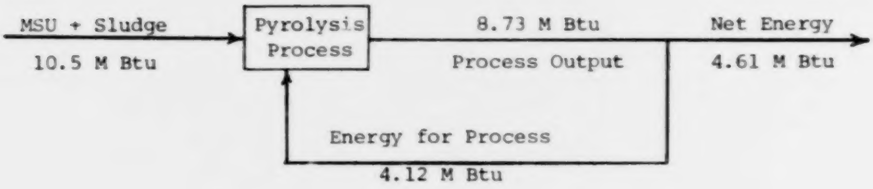
A number of potential markets have been identified for the char resulting from the pyrolysis process: a) solid fuel, b) feed stock for preparing gaseous or liquid fuels and c) substitute for the carbon now being used in carbon and graphite products (activated carbon, charcoal, carbon fillers, carbon risers, etc.).

It appears that the char can be used as a solid fuel and as feed stock for synthetic liquid and gaseous fuels at a market value of about $0.01/lb. With some additional processing the char could also be utilized as an activated carbon, a raw material for charcoal briquettes, a carbon riser in iron and steel production and as fill in non-structural rubber products at a market value of $0.02-$0.04/lb. The major questions regarding these latter applications concern the availability of sufficient market demand. A plant processing 1000 tons of refuse per day could more than saturate many of the potential market opportunities identified (79,500 tons/year). It is therefore, very apparent that each specific char-producing plant built must secure a certified market for its product from one of the applications identified.

Conclusions

The use of chemical treatments to promote carbon char formation at lower pyrolysis temperatures has potential if a reliable market for the char is secured. Laboratory results clearly demonstrated that several chemical treatments can be employed to generate char by low temperature pyrolysis. Both sodium aluminate and ammonium chloride showed promise as char promoters(3). An analysis of the projected economics for a low temperature pyrolysis process reveals that a market providing about $0.017 per pound for the char is necessary to make the process economically viable.

TABLE 1. MATERIAL AND ENERGY BALANCE CALCULATION FOR ONE TON OF MUNICIPAL SOLID WASTE


MSU + Sludge
10.5 M Btu
Pyrolysis Process
8.73 M Btu
Process Output
Net Energy
4.61 M Btu
Energy for Process
4.12 M Btu

Estimated Energy Efficiency

$$\frac{(8.73 - 4.12)\ \text{M Btu}}{10.4\ \text{M Btu}} + 100 = 44\%$$

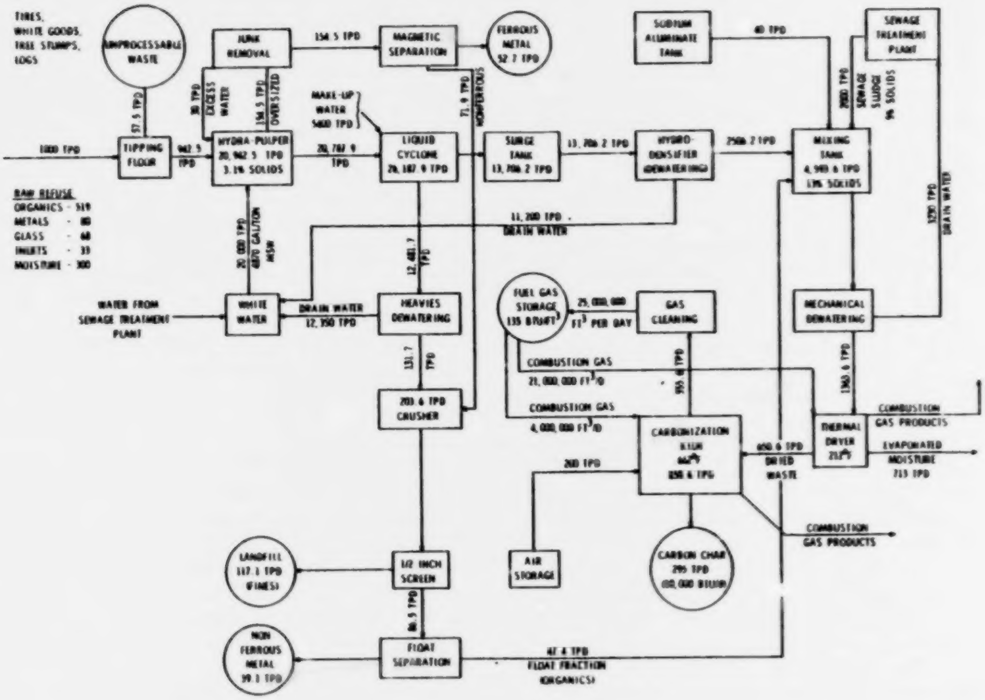

TIRES, WHITE GOODS, TREE STUMPS, LOGS
UNPROCESSABLE WASTE
57.5 TPD
1000 TPD
TIPPING FLOOR
942.5 TPD
RAW REFUSE
ORGANICS - 519
METALS - 80
GLASS - 68
INERTS - 33
MOISTURE - 300
JUNK REMOVAL
30 TPD EXCESS WATER
134.5 TPD OVERSIZED
154.5 TPD
MAGNETIC SEPARATION
FERROUS METAL 52.7 TPD
71.9 TPD NONFERROUS
HYDRA-PULPER 20,942.5 TPD 3.1% SOLIDS
MAKE-UP WATER 5400 TPD
20,787.9 TPD
LIQUID CYCLONE 26,187.9 TPD
SURGE TANK 13,706.2 TPD
13,706.2 TPD
HYDRO-DENSIFIER (DEWATERING)
2506.2 TPD
SODIUM ALUMINATE TANK
40 TPD
SEWAGE TREATMENT PLANT
2000 TPD SEWAGE SLUDGE 9% SOLIDS
MIXING TANK 4,993.6 TPD 13% SOLIDS
3230 TPD DRAIN WATER
11,200 TPD DRAIN WATER
20,000 TPD 4870 GALLON MSW
12,481.7 TPD
WATER FROM SEWAGE TREATMENT PLANT
WHITE WATER
DRAIN WATER 12,350 TPD
HEAVIES DEWATERING
131.7 TPD
203.6 TPD CRUSHER
FUEL GAS STORAGE 135 BTU/FT³
25,000,000 FT³ PER DAY
GAS CLEANING
955.4 TPD
MECHANICAL DEWATERING
1363.6 TPD
COMBUSTION GAS 21,000,000 FT³/D
COMBUSTION GAS 4,000,000 FT³/D
CARBONIZATION KILN 662°F 858.6 TPD
260 TPD
AIR STORAGE
650.6 TPD DRIED WASTE
THERMAL DRYER 212°F
COMBUSTION GAS PRODUCTS
EVAPORATED MOISTURE 713 TPD
COMBUSTION GAS PRODUCTS
CARBON CHAR 295 TPD (10,000 BTU/LB)
LANDFILL 117.1 TPD (FINES)
1/2 INCH SCREEN
86.5 TPD
NON FERROUS METAL 39.1 TPD
FLOAT SEPARATION
47.4 TPD FLOAT FRACTION (ORGANICS)

Figure 1. Flow Plan for a Plant to Convert MSW to a Carbon Char.

TABLE 2. ESTIMATED CAPITAL COSTS (1977 Dollars)

Land (30 Acres at $10,000/acre)	$ 300,000
Site preparation (35% of land cost)	105,000
Equipment, installation and facility construction	18,560,000
Engineering and Design (6% of $18,965,000)	1,138,000
Contingencies (10% of $20,103,000)	2,010,000
Start up and work capital	500,000
SUBTOTAL	22,613,000
Legal and financial costs (2%)	452,000
TOTAL PLANT COST	23,065,000
Municipal revenue bonds for project (financing costs raise bond requirements 12% above capital cost of facility)	25,833,000
Estimated life of facility - 20 years	
TOTAL INTEREST TO BE PAID (8%)	26,397,655
TOTAL CAPITAL COST	52,230,655
ANNUAL CAPITAL COST	2,611,533
ANNUAL THROUGHPUT (tons)	265,200
Capital Cost per ton	9.85

TABLE 3. ESTIMATED ANNUAL OPERATING & MAINTENANCE COSTS (1977 Dollars)

Salaries & Benefits	$ 923,000
Fuel	75,000
Electricity	963,000
Water & Sewer	111,000
Maintenance	696,000
Residue Removal	190,000
Materials & Supplies	1,070,000
Taxes (.75%)	173,000
Insurance & Management Costs ($1.00/ton)	265,000
Total Annual Operating & Maintenance Costs	4,463,000
Operating & Maintenance Cost per ton	16.83

TABLE 4. POTENTIAL REVENUE SOURCES

Revenue Source	Dollars/throughput ton
Tipping fee	$ 8.50/ton
Sludge disposal (200 lbs @ $50/ton)	5.00/ton
Ferrous metal (58 TPD at a net cost of $22.55/ton)	1.31/ton
Stock for aluminum recovery 18 TPD @ net cost of $130/ton	2.34
Subtotal	17.15
Carbon Char (295 TPD market values not established)	?

Another major reservation concerning the use of the carbon char is the lack of familiarity with it as a product. Potential consumers are hesitant to commit themselves to an untried material. To date, the commercialization of char generated from conventional pyrolysis processes has been disappointing, and this serves to moderate enthusiasm for a low temperature pyrolysis process designed to produce a carbon char product.

POWDERED FUEL

Converting the organic fraction of refuse into a finely powdered material offers a number of advantages. In powdered form the refuse is more compatible with the fuel used in suspension fired boilers; it is more easily slurried with oil for firing in liquid fuel units; it is more easily pelletized, and it can be more readily used as a filler.

A number of thermal and chemical treatments have been described in the literature for promoting the conversion of the organic fraction in refuse to a fine powder. Since the major constituent of the organic fraction is cellulose (75%), the treatments are based primarily on the technology of cellulose processing. Most of these processes are chosen to embrittle or degrade the cellulose by reducing the degree of polymerization. In addition to degradation, certain acid treatments appear to promote crosslinking of adjacent molecules, which makes the cellulose rigid and brittle. Heating cellulose in air up to temperatures of 400°F will result in embrittlement. Cellulose treated with formaldehyde also undergoes embrittlement.

Laboratory Studies at UDRI

During this project a number of chemicals were screened for their ability to embrittle paper and other cellulose wastes. A list of the chemicals studied is compiled in Table 5. The results of these initial studies showed that HCl is an extremely strong embrittlement agent. Chlorine gas and thionyl chloride ($SOCl_2$) also were found to be effective embrittlement agents. SO_2 proved to be a moderate embrittlement agent. The effectiveness of SO_2 was greatly enhanced by the inclusion of formaldehyde in the reaction mixture. The experimental arrangement used in these studies is shown in Figure 2.

TABLE 5. EMBRITTLEMENT CHEMICALS EVALUATED

	Chemical
1.	Formalin
2.	Formalin + CO_2
3.	Formalin + NO_2
4.	Formalin + Formic Acid
5.	Formalin + Acetic Acid
6.	Formalin + SO_2
7.	Formalin + HCl
8.	Paraformaldehyde + SO_2
9.	Methylal + SO_2
10.	Acetal + SO_2
11.	HCl
12.	Cl_2
13.	$SOCl_2$

To better define the quantitative requirements for cellulose embrittlement, a second series of experiments was conducted for evaluating the reaction of shredded newsprint with hydrochloric acid, sulfur dioxide-formaldehyde and chlorine gas. The experimental arrangement shown in Figure 2 was used for these experiments.

The results of these experiments showed that a greater quantity of Cl_2 was required for a similar degree of embrittlement as achieved with HCl. In addition, the degree of embrittlement with HCl and Cl_2 is almost unaffected if the quantity of the reactant gases is in excess or equal to the required quantity. If the quantity of reactant gas supplied is less than the required value, poor embrittlement occurs. In a large scale process this would mean additional energy would be required to power the refuse if an insufficient quantity of reactant was used.

The SO_2 requirement for sulfur dioxide-formaldehyde embrittlement was also almost twice as much as HCl. The degree of embrittlement by this process was relatively poor and the results showed that the time required to powder these samples was almost 5 times as much when compared with the powdering time for similar HCl or Cl_2 treated samples. The results from these laboratory experiments showed HCl to be the most suitable reagent as compared to Cl_2 and SO_2.

A further series of experiments studying the embrittlement of shredded newsprint with hydrogen chloride was also conducted.

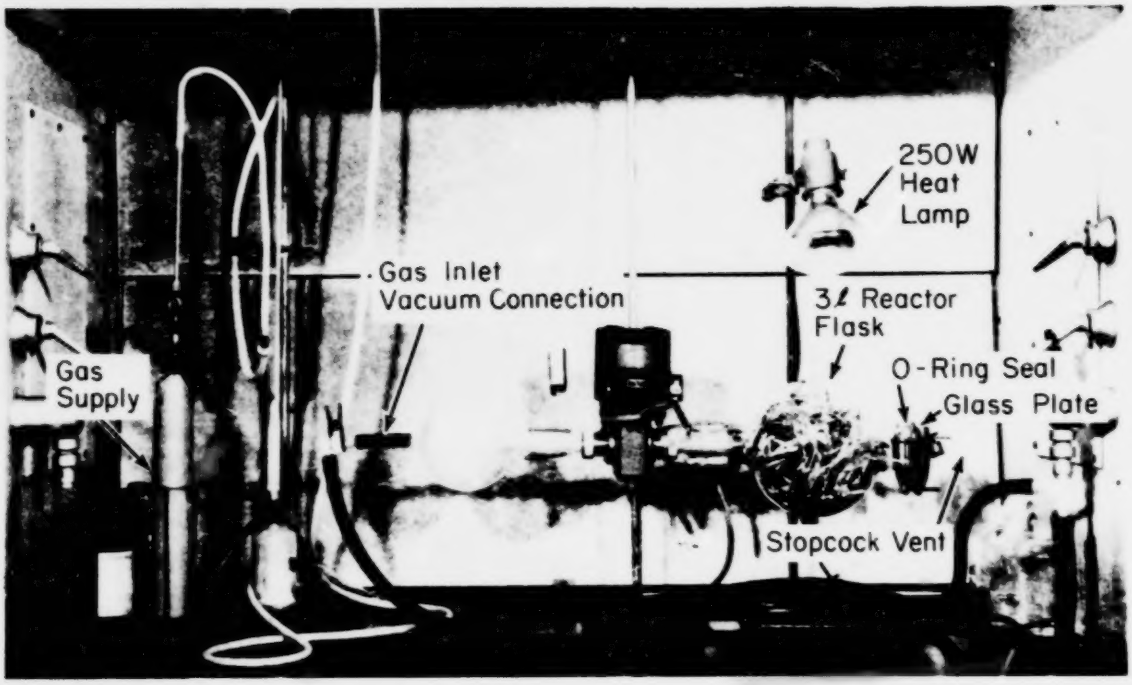


Figure 2. Experimental Arrangement Used for Embrittlement Studies.

using a specially designed pilot size reactor system. The purpose of these experiments was to evaluate process variables with a pilot reactor. Operational problems with the system were analyzed throughout the study and reactor performance was monitored.

The reactor unit used was built by the University of Dayton Research Institute. The reactor system (shown in Figure 3) was designed to process 2 1/2 to 5 lbs. of shredded waste samples with a continuous flow of reactant gases. The reactor was made from a 30 gallon carbon steel drum. The interior of the drum was coated with a 20 mil thickness of Emralon 314 (50% Teflon - 50% Epoxy). The reactor was supported in a Unistrut frame such that it could be loaded and unloaded by tilting it about a horizontal axis between two vertical Unistrut channels. Provisions were made to feed the shredded waste from the top and the lid was sealed with a specially designed rubber gasket and locking ring to prevent leakage. The reactor contents were heated with three 1800 watt drum heaters which were installed on the outside of the reactor. Hydrogen chloride was supplied from a 60 lb. HCl cylinder and N_2 was drawn from an existing N_2 bank. A 5 KW air heater was used to heat the N_2. Two glass rotameters (0. - 3.5 cfm) were used to measure the rate of the reactant gases flowing through the reactor. A perforated stainless steel plate (.33" diameter holes) was installed at the bottom of the reactor to ensure even gas flow. A safety relief valve was installed on top of the reactor. All temperature measurements were made with a digital thermometer.

The scrubber was made from a polyvinyl chloride lined 55 gal. drum in which unreacted HCl in N_2 was neutralized in 84 liters of .15N sodium hydroxide solution. The contacting pattern was improved by dispersing the unreacted gases through a 6" diameter fritted glass funnel into the NaOH solution. Efficiency of the scrubber was tested by neutralizing a measured flow of HCl into the scrubber. The scrubber solution was then titrated with .1N HCl and the results were compared with the flow measurement. A series of tests showed that the scrubber

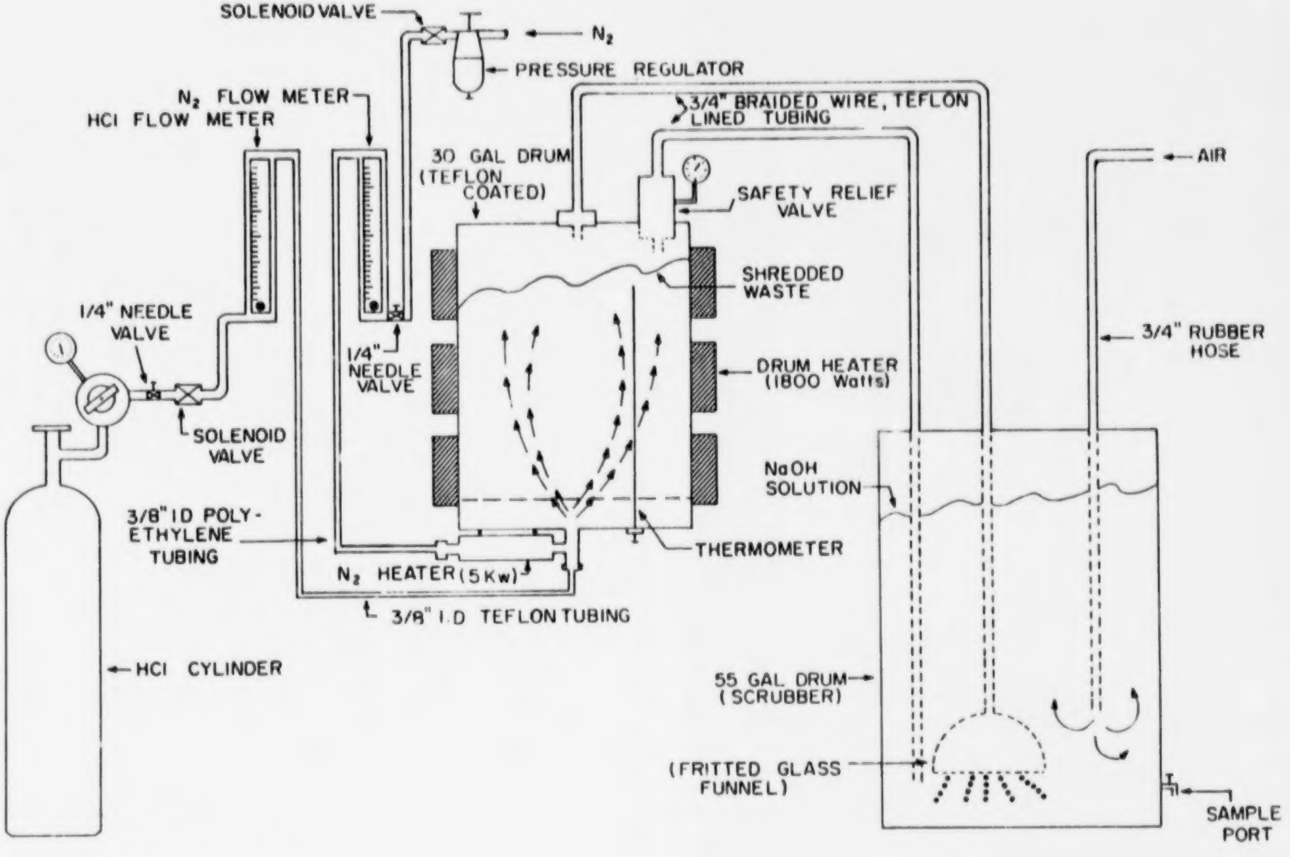

SOLENOID VALVE
N_2
PRESSURE REGULATOR
N_2 FLOW METER
HCl FLOW METER
3/4" BRAIDED WIRE, TEFLON LINED TUBING
30 GAL DRUM (TEFLON COATED)
AIR
SAFETY RELIEF VALVE
SHREDDED WASTE
1/4" NEEDLE VALVE
3/4" RUBBER HOSE
1/4" NEEDLE VALVE
DRUM HEATER (1800 Watts)
SOLENOID VALVE
NaOH SOLUTION
3/8" ID POLY-ETHYLENE TUBING
THERMOMETER
N_2 HEATER (5 Kw)
3/8" I.D TEFLON TUBING
HCl CYLINDER
55 GAL DRUM (SCRUBBER)
(FRITTED GLASS FUNNEL)
SAMPLE PORT

Figure 3. Process Flow Diagram

accounted for an average of 95 percent of the HCl.

A ball mill unit was used to powder the treated shredded paper. The mill consists of two horizontal hard rubber rollers that are 2" in diameter. One of the rollers is chain driven by a 1/4 H/P motor. A 13 qt. ceramic jar is filled with 30 lbs. of 1/2" x 1/2" cylindrical grinding pellets and the treated paper. The charge in the mill is powdered by rotating the jar between the two rollers.

From the data acquired for this series of tests, it is observed that the degree of embrittlement is maximized at:

- the higher treatment temperatures
- the longer reaction times
- minimum moisture contents
- moderate levels of HCl concentration

With the reactor unit used for these tests, the best operating results were obtained at 300°F, six minutes reaction time, and 50 percent (by volume) concentration of HCl with N_2. From some preliminary tests, it is anticipated that the degree of embrittlement could be increased by extending the treatment temperature to between 350°F and 400°F and the reaction time to 8-10 minutes. At temperatures above these values, spontaneous combustion and other difficulties may be encountered. It is also desirable to minimize the quantity of HCl required. It should be noted that a 50 percent reduction in HCl consumption was achieved for the tests conducted in the pilot sized reactor compared to the previous tests conducted in the laboratory sized reactor.

From these embrittlement studies it appears that the HCl serves as a catalyst for a complex embrittlement reaction in the cellulose. The presence of heat enhances the reaction. However, the specific mechanisms are still not completely understood.

Engineering Design

A limited engineering analysis was conducted for a plant to produce a powdered fuel from refuse. The first phase of this study was the development of a design for a plant to process 1,000 tons of refuse per day. The proposed facility would contain two processing lines (each 30 ton/hr capacity) and would operate 20 hours per day, six days per week. In the flow plan developed, the incoming refuse would be screened in a trommel to separate the minus 4" fraction and open the trash bags. The oversized (+4") would be shredded and both fractions passed under magnetic separators to recover the ferrous metal. The nonferrous fraction would be screened in a trommel to separate out the fine fraction (minus 1/2") prior to air classification. The heavy fraction from the air classifier and the fines from the 1/2" trommel are burned in an incinerator and provide the thermal energy required for embrittlement. If aluminum and glass recovery are desired, this would be accomplished by further processing the heavy fraction collected from the air classifier. Aluminum can also be recovered from the incinerated residue, but it would not be of as high a quality. The light fraction obtained from air classification would be embrittled and powdered in an air-swept ball mill (Hardinge Mill). The embrittlement is accomplished by treating the light fraction with heated HCl, in the Hardinge Mill. The powdered material would be swept from the mill entrained in the reactant gas when it is the appropriate size. The data used for developing the flow plan for the proposed facility were obtained from University of Dayton studies(4), Combustion Equipment Associated data reported in U. S. Patent 3,961,913(5), and NCRR studies for New Orleans(6). The flow plan established for a facility to produce fine powdered fuel from refuse is presented in Figure 4. The calculations developed for the material balance used in the flow plan are presented in Table 6. The flow plan and material balance developed in this phase of the program served as the basis for determining equipment specifications and operating requirements. This information in turn was used to develop the economic analysis for the proposed plant.

Economic Analysis

A preliminary economic analysis was prepared for the powdered fuel process. The analysis is based on the process flow plan developed (Figure 4). Revenues are anticipated from: a) tipping fee, b) sale of recovered metals, c) sale of powdered fuel.

A summary of the calculations developed for the capital and operating costs are presented in Tables 7 and 8 respectively. A summary of potential revenues are presented in Table 9.

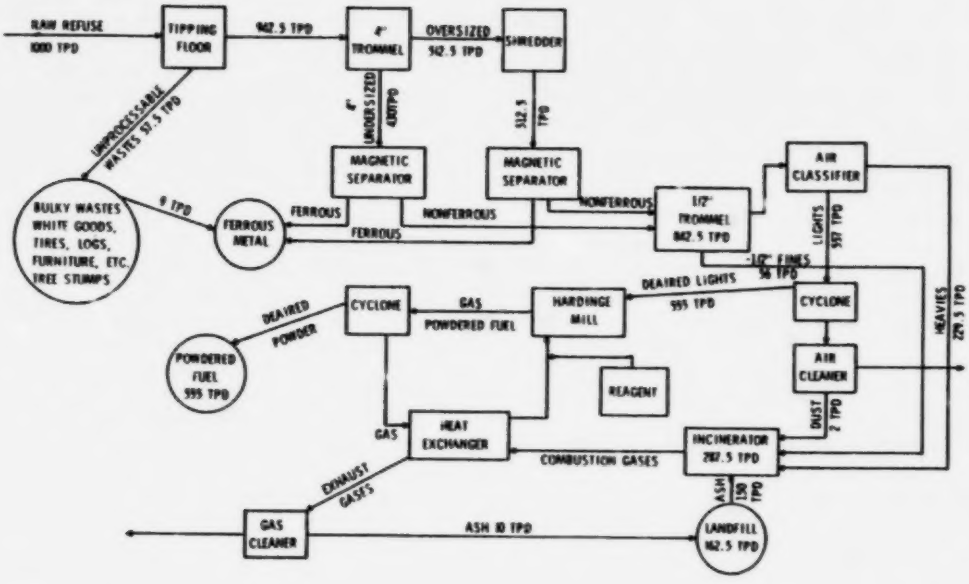

RAW REFUSE
1000 TPD
TIPPING FLOOR
942.5 TPD
4" TROMMEL
OVERSIZED
512.5 TPD
SHREDDER
4" UNDERSIZED
430TPD
512.5 TPD
UNPROCESSABLE WASTES 57.5 TPD
MAGNETIC SEPARATOR
MAGNETIC SEPARATOR
BULKY WASTES
WHITE GOODS,
TIRES, LOGS,
FURNITURE, ETC.
TREE STUMPS
9 TPD
FERROUS METAL
FERROUS
NONFERROUS
FERROUS
NONFERROUS
1/2" TROMMEL
842.5 TPD
AIR CLASSIFIER
LIGHTS 557 TPD
-1/2" FINES 56 TPD
DEAIRED LIGHTS
555 TPD
CYCLONE
HARDINGE MILL
GAS
POWDERED FUEL
CYCLONE
DEAIRED POWDER
POWDERED FUEL 555 TPD
REAGENT
AIR CLEANER
HEAVIES 229.5 TPD
DUST 2 TPD
HEAT EXCHANGER
GAS
INCINERATOR
287.5 TPD
COMBUSTION GASES
EXHAUST GASES
ASH 150 TPD
GAS CLEANER
ASH 10 TPD
LANDFILL
162.5 TPD

Figure 4. Resource Recovery Plant to Produce Powdered Fuel.

TABLE 6. MATERIAL BALANCE FOR A POWDERED FUEL PROCESS

			Trommel 4"		Magnetic Separation		Trommel 1/2"		Air Classification				
	Incoming (1000 TPD)	Unprocessable Waste (57.5)	-4" (430)	+4" (512.5)	Ferrous (100)	Nonferrous (842.5)	-1/2" (56)	+1/2" (786.5)	Lights (557)	Heavies (229.5)	Incineration (287.5)	Landfill (162.5)	Powdered Fuel (555 TPD)
Refuse													
Organic Fraction	750	40	225	485	22	688	45	643	553	90	135	10	553
Metal	100	10	67	23	76.5	13.5	0.5	13	3.5	9.5	11.5	11.5	2
Ferrous	85	9	57	19	75	1	-	1	-	1	1	1	-
Nonferrous	15	1	10	4	1.5	12.5	0.5	12	3.5	8.5	10.5	10.5	2
Glass and other inerts	150	7.5	138	4.5	1.5	141	10.5	130.5	0.5	130	141	141	-

TABLE 7. ESTIMATED CAPITAL COSTS (1977 Dollars)

Land (30 Acres @ $10,000/acre)	$ 300,000
Site Preparation (35% of land cost)	105,000
Equipment, Installation & Facility Construction	15,456,000
Engineering & Design (6% of $15,681,000)	952,000
Contingencies (10% of $16,813,000)	1,681,000
SUB TOTAL	18,494,000
Legal & Financial Costs (2%)	370,000
TOTAL PLANT COSTS	$18,864,000
Municipal Revenue Bonds for the Project (1.12 plant cost)	$21,128.000
Annual Interest Rate for 20 years @ 8%	1,095,534
Total Interest to be paid	21,910,669
Total Capital Cost	43,038,669
Annual Capital Cost	2,151,934
Capital Cost Per Ton	8.12

TABLE 8. ESTIMATED ANNUAL OPERATING AND MAINTENANCE COSTS (1977 Dollars)

Salaries and Benefits	$ 872,000
Fuel	100,000
Electricity	437,000
Water and Sewer	3,000
Maintenance	666,000
Residue Removal	250,000
Materials and Supplies	711,000
Taxes (.75%)	142,000
Insurance and Management Costs ($1/ton)	265,000
Total Annual Operating & Maintenance Cost	$3,446,000
Operating and Maintenance Cost Per Ton	12.99

TABLE 9. POTENTIAL REVENUE SOURCES

Revenue Source	Dollars/Throughput Ton
Tipping Fee	8.50
Ferrous Metal (86 TPD @ a net cost of $22.55/ton)	1.94
Powdered Fuel (550 TPD)	??
Cost/ton	21.11
Cost needed for sale of fuel to break even	10.67

$.01/lb of powdered fuel @ 7,500 Btu/lb - 1.33/M Btu

From the analysis developed, a total operating cost per throughput ton of MSW was calculated to be \$21.11. A potential revenue of \$10.44/throughput ton was calculated for the sale of ferrous and the tipping fee. To break even, the powdered fuel would have to sell for about \$0.01/lb or about \$1.33/million Btu.

Conclusions

The use of powdered fuel prepared from the embrittlement of cellulose waste offers a number of advantages:

a) It is more compatible with powdered coal-fired boilers and will have better combustion characteristics than conventional RDF.

b) It is more readily densified into pellets and will produce less wear on the extrusion dies.

c) It can be slurried with oil for firing in oil fired units.

d) It can be used as the feed stock for further chemical or thermal treatments like hydrolysis, hydrogenation, gasification, etc.

In the work to date we have identified a number of chemical treatments for cellulose embrittlement and evaluated their effectiveness in laboratory studies. In addition, a preliminary design for a resource recovery plan to produce powdered fuel was developed. This design plan was the basis for a preliminary economic analysis. From the data developed, it was calculated that the powdered fuel would have to sell for about \$0.01/lb for a facility having a tipping fee of \$8.50.

FUTURE WORK

Laboratory studies at UDRI have demonstrated that a number of treatments can be used for the embrittlement of cellulose wastes to produce a powdered fuel. Although the process variables have been determined and a preliminary engineering design and economic analysis have been established for the production of a P-RDF, there is need for further research. A number of studies to better characterize the P-RDF as a fuel or fuel component are planned. In addition, studies to extend the utilization of embrittlement in resource recovery processes are planned.

A compilation of the tasks to be initiated in the next phase of the project are presented below:

(a) Combustion analysis of P-RDF fuel.

(b) Oil/P-RDF slurry development.

(c) Embrittlement studies on unprocessed raw refuse.

(d) Embrittlement studies on wood product and crop wastes.

(e) Investigation of partial embrittlement techniques for preparing RDF flakes.

(f) Economic reevaluation of embrittlement processes.

Although P-RDF has been characterized, performance in burn tests has not been established. Therefore, combustion studies of the powdered fuel prepared from the embrittlement of RDF will be conducted in a test unit with a burner for pulverized coal.

Another area of major interest is the suspension of the P-RDF in an oil. The handling and shipment of a powdered fuel to its point of use presents some problems - a major one being safety hazards arising from the potential explosion characteristics of a finely powdered material. A possible solution to this problem is storing, transporting, and burning the powdered fuel in an oil slurry. The techniques used for powder suspension will initially be based on the work done in developing mixtures of powdered coal in oil. Once an effective P-RDF/oil slurry is developed, mixtures of 10, 25, and 50 percent powder/oil slurries will be prepared. These slurries will be subjected to combustion tests. It is expected that an air atomizing burner unit would be used for the proposed combustion tests.

Another important task will be the evaluation of the economics for the embrittlement process. The results of the combustion tests and additional research tasks will be utilized to reevaluate the economics for powder preparation and its utilization as a fuel.

REFERENCES

1. Harendza-Harinxma, A. Method of Carbonizing a Substance Comprising Cellulose. U. S. Patent 3,961,025, 1976.

2. Wittman, T. J. et al. A Technical, Environmental and Economic Evaluation of the Wet Processing System for the Recovery and Disposal of Municipal Solid Waste. U. S. Environmental Protection Agency, Washington, D. C., 1975. 217 pp.

3. Hecht, N. L., Duvall, D. S., Fox, B. L., "Investigation of Advanced Thermal-Chemical Concepts for Obtaining Improved MSW-Derived Products," EPA Report 600/7-78-143, Environmental Protection Agency, Cincinnati, OH, August 1978.

4. Hecht, N. L. et al. Design for a Resource Recovery Plant for AMAX Inc. University of Dayton, Dayton, OH, 1974.

5. Brennemon, R. S. and Clancy, J. J. Process for Treating Organic Wastes and Products Thereof. U. S. Patent 3,961,913, June 8, 1976.

6. National Center for Resource Recovery, Inc., New Orleans Resource Recovery Facility. Implementation Study: Equipment, Economics and Environment. National Center for Resource Recovery, Inc., Washington, D. C., 1977.

ENVIRONMENTAL IMPACT OF RESOURCE RECOVERY

Judith G. Gordon

MITRE Corporation
Metrek Division
McLean, Virginia

ABSTRACT

This report summarizes an assessment of the impact of resource recovery on the environment. The study examined the enviornmental effects that will derive from municipal solid waste disposal in 1990 and the changes in these effects that will result from implementation of resource recovery from municipal solid waste. The direct effects of municipal solid waste disposal as well as the secondary effects of substituting recovered materials for raw materials in the production of steel, aluminum, glass, and energy were considered. The methodology used in the analysis and the findings are discussed in this paper.

INTRODUCTION

Interest in resource recovery from municipal solid waste has increased in recent years, and resource recovery is generally considered a worthwhile goal. Proponents of resource recovery maintain that establishment of resource recovery facilities should be encouraged by the Federal government. However, in the absence of an assessment of the effects on the environment of resource recovery, it was not known what these effects would be nor the net impact of resource recovery on the environmental effects of municipal solid waste disposal. This study was initiated with just such an objective -- to determine quantitatively the environmental effects of resource recovery from the perspective of the overall nationwide impacts.

The objectives of this study were, therefore, to determine:

(a) The direct effects on the environment of municipal solid waste disposal and of resource recovery from municipal solid waste,

(b) The secondary effects of resource recovery resulting from substitution of recovered materials for virgin materials, i.e., environmental effects and impact on energy, and

(c) The potential benefits of resource recovery in mitigating the adverse environmental effects of municipal solid waste disposal.

The scope of the study was determined to some extent by the selected definitions of terms. Municipal solid waste was defined as being comprised of residential and commercial solid waste, i.e., the urban refuse that is normally handled by municipalities. In resource recovery, recovery will be achieved by front-end processing and by mass burning followed by materials recovery from the residue; source separation was not considered. Scrap ferrous metals, aluminum, and glass will be recovered from municipal solid waste and will be substituted for virgin materials in the production of steel, aluminum products, and glass containers. The energy content of municipal solid waste will also be recovered, replacing some coal combustion in energy production.

TABLE 1

1990 SCENARIOS FOR HANDLING OF MUNICIPAL SOLID WASTE

DISPOSAL METHOD/ PROCESS	WITHOUT RESOURCE RECOVERY		WITH RESOURCE RECOVERY	
	%	tons	%	tons
Mass Burning	5	10,000,000	5	10,000,000
Landfill	95	187,000,000	80	157,000,000
Resource Recovery				
Front-end processing with materials separation and combustion of RDF			7.5	15,000,000
Mass burning of raw refuse with energy recovery (waterwall incineration) and materials recovery from residue			7.5	15,000,000
TOTAL		197,000,000		197,000,000

The analysis was based on the year 1990 which was selected because it is the earliest date by which the number of fully operational resource recovery facilities will be sufficient for resource recovery to have a significant impact on the environment. Two scenarios were developed for municipal solid waste disposal in 1990 -- one without and the other with resource recovery (Table 1).

METHODOLOGY

Environmental Effects

The factors considered in this study were air pollutants, water pollutants, landfill capacity, and energy conservation.

Analysis of air pollutants was the most comprehensive because of the availability of data on pollutant emissions from municipal solid waste disposal and resource recovery - related activities. Data sources were primarily the United States Environmental Protection Agency (1) and studies of the Ames, Iowa, Solid Waste Recovery System (2,3). Data were presented for emissions of particulates, oxides of sulfur and nitrogen, carbon monoxide, hydrocarbons, aldehydes, chlorides, and ammonia as well as for landfill generation of carbon dioxide and methane. Pollutant emissions from municipal solid waste disposal, from materials production, and from energy production were quantified.

Analysis of water pollutants pertained only to the direct effects of municipal solid waste disposal without and with resource recovery; the secondary effects of resource recovery, i.e., pollutants from materials production and energy production, were not included in this study. Data sources were incinerator studies (4,5,6) and leachate studies (7,8,9); equilibrium modeling of leachate was used to project pollutant concentrations in 1990 (10,11,12). Data were presented for various metals and other elements as well as several anions and compounds. Quantities of pollutants in wastewater discharges to surface waters and in leachate* from landfills were estimated.

The requirements for landfill capacity for disposal of municipal solid waste were estimated. Estimates were made for the two scenarios -- without and with resource recovery.

The effects of resource recovery on energy conservation were quantified. Energy conservation in materials production from recovered materials rather than from virgin materials and energy recovery from municipal solid waste were the aspects analyzed.

Analysis

The methodology developed for quantifying the environmental effects of municipal solid waste disposal and resource recovery is based on two components: "effect factors" and "quantifiers." The effect factor pertains to the particular environmental effect, or component thereof, that is being considered and provides data on that effect in terms of unit measure. Examples of effect factors are the emission factor for an air pollutant (per ton of municipal solid waste incinerated or ton of steel produced), the concentration of a pollutant in landfill leachate, the density of landfilled raw refuse, and the energy requirement for producing a ton of steel from scrap ferrous metal. Quantifiers are estimated from available data and are based on specific assumptions. Examples of quantifiers are the quantities of municipal solid waste, leachate, and recovered glass, and the quantity of energy that is recoverable from municipal solid waste.

An illustration of the methodology is quantification of the direct effects of municipal solid waste disposal. The effect factors required for the determination are presented in Table 2 (12). The quantifiers depend on the scenario, i.e., without or with resource recovery. The quantities of pollutants that will derive from disposal of municipal solid waste (MSW) in 1990 are calculated from the following equations.

Calculation of Quantities of Air Pollutants That Will Be Emitted during Mass Buring of MSW

$$Q_p = Ef_p \times M_I \times f \qquad (1)$$

where Q_p = quantity of a pollutant that will be emitted (tons)

Ef_p = emission factor for that pollutant (pounds/ton MSW incinerated)

M_I = mass of MSW that will be disposed of by incineration (tons)

f = conversion factor (from pounds to tons)

= 1/2000

Calculation of Quantities of Gases That Will Be Generated in Landfills in 1991 by MSW Landfilled in 1990

$$Q_p = G_p \times f_1 \times M_L \times D_p \times f_2 \qquad (2)$$

where Q_p = quantity of the gas that will be generated in the one year from the landfilled MSW (tons)

G_p = maximum quantity of gas generation over 25 years (cubic feet/ton MSW)

f_1 = time factor (one year out of 25 years during which gas is generated)

= 1/25

M_L = mass of MSW that will be landfilled in 1990 (tons)

D_p = density of the gas (pounds/standard cubic foot)

f_2 = conversion factor (from pounds to tons)

= 1/2000

---

*The total pollutant loading in leachate does not represent the quantities of pollutants that eventually enter the ground and/or surface waters.

TABLE 2

PROJECTED CONCENTRATIONS OF POLLUTANTS FROM MUNICIPAL SOLID WASTE (MSW) DISPOSAL IN 1990[a]

	SOURCE							
	MASS BURNING		LANDFILL OF MSW		ENERGY RECOVERY FROM RDF		LANDFILL OR RESIDUE	
RECEIVING MEDIUM/POLLUTANT	STACK EMISSIONS (lb/ton)	WASTE-WATER[b] (ppm)	LEACHATE[c] (ppm)	GASES (cu ft/ton in 25 yrs)	STACK EMISSIONS[d] (lb/ton RDF)	WASTE-WATER[e] (ppm)	LEACHATE[f] (ppm)	GASES (cu ft/ton)
AIR								
Particulates	1.02				1.28			
SO_x (as SO_2)	2.02				4.43			
NO_x	1.14 - 3.43				1.54			
CO	0.69 - 2.07				NA			
Hydrocarbons (as CH_4)	0.2				0.0036			
Aldehydes (as Formaldehyde)	0.0004 - 0.01				-0.36			
Chlorides (as HCl)	3.71 - 7.41				7.81			
CO_2	NA[g]			4560	NA			0
CH_4				4560				0
WATER								
Aluminum		20.4	NA			~0	NA	
Barium		5.0	NA			5.0	NA	
Cadmium		NA	0.03			NA	0.00578	
Calcium		42	60 - 7200			42	26.8	
Chloride		30 - 193	5 - 2467			30 - 193	NA	
Chromium		0.13	1.05			0.13	NA	
Copper		0.02	1.30			~0	1.26	

TABLE 2 (Concluded)

	SOURCE							
	MASS BURNING		LANDFILL OF MSW		ENERGY RECOVERY FROM RDF		LANDFILL OF RESIDUE	
RECEIVING MEDIUM/POLLUTANT	STACK EMISSIONS (lb/ton)	WASTE-WATER[b] (ppm)	LEACHATE[c] (ppm)	GASES (cu ft/ton in 25 yrs)	STACK EMISSIONS[d] (lb/ton RDF)	WASTE-WATER[e] (ppm)	LEACHATE[f] (ppm)	GASES (cu ft/ton)
WATER (cont)								
Iron		0.3	810			~0	0.0138	
Lead		0.5	1.4			~0	0.00425	
Magnesium		0	17 - 15,600			0	13.2	
Manganese		0.30	0.06 - 125			~0	2.08	
Nickel		NA	1.20			NA	0.0220	
Phenols		0.005	NA			0.005	NA	
Phosphate		2 - 9	NA			2 - 9	NA	
Potassium		NA	29 - 3770			NA	NA	
Sodium		NA	34 - 7700			NA	NA	
Sulfate		32 - 50	1 - 3770			32 - 50	11.9	
Zinc		1.0	155			~0	0.138	

[a] Source: Gordon, 1978 (Reference 12).

[b] Incinerator wastewater discharged to surface waters.

[c] Concentrations in leachate, not in groundwater.

[d] Portion of cofiring emissions that is attributable to the RDF fraction.

[e] Based on pollutants in incinerator wastewater.

[f] Based on equilibrium composition of a hypothetical liquid-phase/solid-phase system.

[g] NA: Data not available.

Calculation of Quantities of Pollutants That Will Be Discharged to Surface Waters in Incinerator Wastewater

$$Q_P = C_P \times Q_W \times M_I \qquad (3)$$

where Q_P = quantity of a pollutant that will be discharged in incinerator wastewater (tons)

C_P = concentrations of that pollutant in the effluent

Q_W = water requirement (tons/ton MSW incinerated)

M_I = quantity of MSW that will be incinerated (tons)

Calculation of Quantities of Pollutants That Will Be Present in Leachate from Landfilled MSW (based on reported ranges of concentrations)

$$Q_P = C_P \times Q_L \times f_1 \times f_2 \qquad (4)$$

where Q_P = quantity of a pollutant that will be present in landfill leachate (tons)

C_P = range of concentration of that pollutant in the leachate (ppm)

Q_L = quantity of landfill leachate (10^9 gallons)

f_1 = conversion factor (from ppm to pounds/billion gallons)

= 8345

f_2 = conversion factor (from pounds to tons)

= 1/2000

Calculation of Quantities of Pollutants That Will Be Present in Leachate from Landfilled MSW (based on data for a single landfill)

$$Q_P = C_P \times Q_L \times f_1 \times f_2 \times f_3 \qquad (5)$$

where Q_P = quantity of a pollutant that will be present in landfill leachate (tons)

C_P = concentration of that pollutant in the leachate

Q_L = quantity of leachate from the one landfill

= 20,000 cubic meters/month

f_1 = conversion factor (from month to year)

= 12

f_2 = conversion factor (from grams to tons)

= 1.102×10^{-6}

f_3 = factor for extrapolating from one landfill to the national landfill area

= 600,000/300

For calculations of pollutant quantities for the scenario with resource recovery, some of the equations are used more than once -- with appropriate values assigned to the effect factors and quantifiers -- in order to account for all sources of a given pollutant (e.g., leachate will be derived from landfilled raw refuse as well as from landfilled resource recovery residue).

Similar methodology is used to calculate all the other effects including pollutants emitted during materials production and during energy production, energy conservation in materials production from recovered scrap materials, energy recovery from municipal solid waste, and landfill capacity requirements. Total effects of each type (e.g., direct effects of municipal solid waste disposal and secondary effects of resource recovery) are calculated by summing the individual effects. The net changes that will result from implementation of resource recovery are calculated by determining the differences in effects that would derive from the two scenarios.

The equations used in the calculations are listed and explained in Appendix A of Reference 12. Appendix A also includes sample calculations that are based on (a) the effect factors given in the tables, and (b) the quantifiers derived from data and assumptions that are presented in the tables and accompanying discussion.

RESULTS AND DISCUSSION

The effects on the environment of resource recovery from municipal solid waste were determined for a specific scenario for resource recovery implementation (Table 1). In addition, numerous other assumptions were made which directly affected the results of this study. Consequently, the findings are valid only for the particular conditions specified in the assumptions. Any change in the data and/or the assumptions will alter the results. The methodology developed in this study is readily applicable for recalculation of the environmental effects of resource recovery that would result from any changes in data and assumptions.

Assumptions

It is impossible to list all the assumptions in this summary of the study, and the reader is referred to the original report (12). Some of the most important assumptions that were made for the year 1990 were:

- About 197,000,000 tons of municipal solid waste will be generated in the United States.
- The scenarios for municipal solid waste disposal without and with resource recovery (Table 1) are valid.
- The effect factors are representative of actual operating conditions.
- The 1975-to-1990 increases in landfill area and in leachate from municipal landfills will be proportional to the increases in required landfill capacity under each scenario.
- Recovery efficiencies for ferrous metals, aluminum, and glass will be the same for front-end separation and recovery after mass burning.
- All the materials recovered from municipal solid waste will be recycled and will replace virgin materials in materials production.
- Steel, aluminum, and glass will be produced by the same processes in the same relative quantities and at the same production efficiencies as in 1975.
- Energy requirements for materials production from virgin and from recovered materials will be the same as in 1975.
- Energy recovery from municipal solid waste will amount to 161.4 x 10^{12} Btu and will replace 0.8% of the power that otherwise would be generated by coal combustion.

Findings

The various effects of implementation of resource recovery in accordance with the scenario for 1990 are summarized in Tables 3, 4, and 5. Table 3 summarizes the effects on air emissions, Table 4, the effects on water resources, and Table 5 the miscellaneous effects. The environmental effects of resource recovery from municipal solid waste are primarily favorable.

Table 3 presents the direct effects and the secondary effects of resource recovery on air emissions as well as the summed -- i.e., net -- effects. Net emissions of all but three of the air pollutants considered will be reduced. Emissions of carbon monoxide will be reduced in 1990 by about 2,300,000 tons and emissions of carbon dioxide, NO_x, and methane by about 310,000 tons, 150,000 tons, and 114,000 tons, respectively. Smaller reductions will occur in emissions of SO_x (~23,000 tons) and hydrocarbons (~7200 tons). There will be slight increases in the quantities of total particulates (~1000 tons) and aldehydes (~2500 tons) emitted and a larger increase (~ 140,000 tons) in chloride emissions. Emissions of particulate and gaseous fluorides will not be affected by resource recovery.

In Table 4 are listed the direct effects of municipal solid waste disposal on the water resources. The quantities of pollutants that will be discharged to surface waters in incinerator wastewater effluent will increase because more municipal solid waste will be incinerated with implementation of the scenario for resource recovery. With resource recovery from municipal solid waste, smaller

TABLE 3
SUMMARY OF THE EFFECTS ON AIR EMISSIONS OF IMPLEMENTATION OF RESOURCE RECOVERY IN ACCORDANCE WITH THE SCENARIO FOR 1990[a]

POLLUTANT	DIRECT EFFECTS[b]	SECONDARY EFFECTS[c]		NET EFFECTS[e]
	DISPOSAL OF MSW	MATERIALS PRODUCTION	ENERGY PRODUCTION[d]	
Particulates, total	+14,850	-10,654	+4050	+1046
SO_x (as SO_2)	+40,050	-5155	-32,800	-22,805
NO_x (as NO_2)	+(17,200 to 34,400)	-51	-(156,980 to 174,800)	-(131,296 to 166,316)
CO	+(5175 to 15,550)	-2,305,000	-(210 to 11,140)	-(2,289,660 to 2,310,965)
Hydrocarbons (as CH_4)	+1500	-5385	-3340	-7245
Aldehydes (as formaldehyde)	-(1900 to 1970)	NA[f]	+ 2470	+(2525 to 2595)
Chlorides (as HCl)	+(71,800 to 99,450)	NA	+(81,780 to 110,940)	+(109,630 to 166,440)
Particulate Fluorides	0	0	NA	0
Gaseous Fluorides	0	0	NA	0
NH_3	NA	-231	NA	-231
CO_2	-310,000	NA	NA	-310,000
CH_4	-114,000			-114,000

[a] Tons that will be emitted in 1990.

[b] Direct effects of resource recovery on environmental impact of municipal solid waste disposal. Includes emissions attributable to refuse-derived fuel (RDF).

[c] Indirect environmental effects of using recovered materials to replace virgin materials in materials and energy production. Does not include environmental effects of mining virgin materials or transporting virgin and recovered materials.

[d] Includes pollutants from cofiring of coal and RDF. Credit is given for emissions from coal not burned.

[e] Sum of the direct and indirect effects of resource recovery corrected to eliminate double counting of the emissions attributable to RDF (which are included in both direct and secondary effects). "Plus" indicates an increase in emissions, "minus" a decrease.

[f] NA: Data not available.

TABLE 4

SUMMARY OF THE EFFECTS ON WATER RESOURCES OF IMPLEMENTATION OF RESOURCE RECOVERY IN ACCORDANCE WITH THE SCENARIO FOR 1990[a]

POLLUTANT	DIRECT EFFECTS OF MSW DISPOSAL	
	DISCHARGES TO SURFACE WATER[b]	POLLUTANTS IN LANDFILL LEACHATE[c]
Aluminum	+918	NA[d]
Barium	+394	NA
Cadmium	NA	-3
Calcium	+3310	-(4400 to 540,000)
Chloride	+(2365 to 15,210)	-(375 to 183,500)
Chromium	+10	-89
Copper	+1	-112
Cyanide	0	NA
Iron	+14	-69,500
Lead	+23	-120
Magnesium	0	-(1210 to 1,170,000)
Manganese	+14	+5 to -9400
Nickel	NA	-103
Phenols	0	NA
Phosphate	+(158 to 709)	NA
Potassium	NA	-(2150 to 285,000)
Sodium	NA	-(2550 to 580,000)
Sulfate	+(2520 to 3940)	-(25 to 285,000)
Zinc	+45	-13,250

[a] "Plus" indicates an increase in pollutant quantities, "minus" a decrease.

[b] Net difference in tons of pollutants that will be discharged in 1990. Assumes water recirculation and use of 3 tons of water per ton of incinerated municipal solid waste or ton of refuse-derived fuel.

[c] Net difference in tons of pollutants that will be present in landfill leachate in 1990. Assumes 90 x 10^9 gallons of leachate from landfilled raw municipal solid waste and 1 x 10^9 gallons of leachate from landfilled resource recovery residue.

[d] NA: Data not available

quantities of pollutants will be present in landfill leachate. The decreases will range from 3 tons of cadmium, a minimum of 25 tons of sulfate and about 100 tons of chromium, copper, lead, and nickel to more than 1,000,000 tons of magnesium. Because of various factors, (e.g., soil interactions), the total pollutant loading in landfill leachate does not enter the ground and/or surface waters. In the absence of data on leachate contributions to the pollutant loadings of ground and surface waters, the net effects of resource recovery on the water resources cannot be determined.

The miscellaneous effects of resource recovery -- specifically the requirements for landfill capacity and energy considerations -- are summarized in Table 5. The requirement for landfill capacity to dispose of municipal solid waste and the residues from mass burning and resource recovery will be decreased by about 44,260 acre-feet as a result of the direct effects of resource recovery. The landfill capacity needed with resource recovery will be about 85 percent of the capacity that would be required if there were no resource recovery from municipal solid waste. The secondary effects of resource recovery will reduce the quantities of other solid wastes requiring disposal; however, the reductions in quantities of solid wastes from mining of virgin materials, from materials production, and from coal combustion were not quantified in this study.

Data on energy recovery from municipal solid waste and energy conservation in materials production from recovered materials are summarized in Table 5. Energy derived from municipal solid waste in 1990 will amount to 161.4 x 10^{12} Btu (28.8 x 10^{6} barrels of crude oil equivalent). Energy conservation that will accrue from substitution of recovered for virgin materials in the production of steel, aluminum, and glass will be about 75.2 x 10^{12} Btu (13.4 x 10^{6} BCOE). The total energy savings that could be realized from resource recovery from municipal solid waste will therefore be about 236.6 x 10^{12} Btu or 42.3 x 10^{6} barrels of crude oil equivalent.

Discussion

The findings of this study confirm the expectations that the impacts of resource recovery on the environment will be beneficial. Nevertheless, an equally important benefit derived from this study is probably the development of a methodology for assessing these impacts.

The importance of the methodology lies in its versatility and its applicability to the study of the environmental effects of resource recovery. With the equations developed for this study, it is possible to calculate environmental effects easily and rapidly. Therefore, although the particular findings presented here may become obsolete as new data become available, this methodology provides the means for recalculation of the environmental effects.

Suggested uses of this methodology include:

- Filling in gaps in this study that resulted from unavailable data,
- Extending the analysis to environmental effects not considered in this study (e.g., the secondary effects of resource recovery on the water resources),
- Recalculating and updating the environmental effects of resource recovery as additional and better data become available, and
- Performing sensitivity analyses to determine the differences that would result from changes in the assumptions and other variables.

TABLE 5

SUMMARY OF THE MISCELLANEOUS EFFECTS OF IMPLEMENTATION OF RESOURCE RECOVERY IN ACCORDANCE WITH THE SCENARIO FOR 1990

EFFECT	DIRECT EFFECTS	SECONDARY EFFECTS		TOTAL
	MSW DISPOSAL	MATERIALS PRODUCTION	ENERGY PRODUCTION	
Requirement for Landfill Capacity (acre-feet)	-44,260[a]	b	b	-44,260[a]
Energy Recovery				$236,643,000 \times 10^6$ Btu 42,258,000 BCOE[c]
(Btu)			$161,400,000 \times 10^6$	
(BCOE)[b]			28,821,000	
Energy Conservation				
(Btu)		$\sim 75,243,000 \times 10^6$		
(BCOE)[b]		13,436,000		

[a] "Minus" indicates a decrease in requirement for landfill capacity.

[b] Solid wastes from mining of virgin materials, from materials production, and from coal combustion were not included in this study.

[c] BCOE: Barrels of crude oil equivalent.

ACKNOWLEDGMENTS

This study was prepared for the Processing Branch in the Solid and Hazardous Waste Research Division of the Municipal Environmental Research Laboratory of the United States Environmental Protection Agency in Cincinnati, Ohio under Contract 68-03-2596. Dr. Albert J. Klee was Project Office. Mr. William Lowenbach performed the analysis of leachate data and the equilibrium modeling estimation of leachate quality.

REFERENCES

1. United States Environmental Protection Agency. Compilation of Air Pollutant Emission Factors, 2nd edition. #AP-42, with Supplements. Office of Air and Waste Management, Office of Air Quality Planning and Standards, Research Triangle Park, North Carolina, February, 1972.

2. Hall, J.L., A.W. Joensen, G.A. Severns, D.B. Van Meter, and H. Shanks. Emissions from Stoker Fired Boilers Using Coal-RDF Mixtures. Paper presented at the 8th Biennial Waste Processing Conference, Chicago, Illinois, May 7-10, 1978.

3. White, Robert. Midwest Research Institute, Kansas City, Missouri, Communication of unpublished data, June 8, 1978.

4. Achinger, W.C., and L.E. Daniels. Seven Incinerators. #SW-51ts.1j. Office of Solid Waste, U.S. Environmental Protection Agency, Washington, D.C., 1970.

5. Brinkerhoff, R.J., and W.C. Achinger. The Braintree, Massachusetts, Municipal Incinerator. #SW-108, pp. 37-39. Office of Solid Waste, U.S. Environmental Protection Agency, Washington, D.C., 1973.

6. Weinstein, N.J. Municipal-Scale Thermal Processing of Solid Wastes. #EPA/530/SW-133c, pp. 203-212. Office of Solid Waste, U.S. Environmental Protection Agency, Washington, D.C., 1977.

7. Chian, E.S.K., and F.B. DeWalle. Sanitary Landfill Leachates and Their Treatment. *Journal of the Environmental Engineering Division, Proceedings of the American Society of Civil Engineers*, *102*(EE2): 411-431, April 1976.

8. Johansen, O.J., and D.A. Carlson. Characterization of Sanitary Landfill Leachates. *Water Research* (London), *10*:1129-1134 (1976).

9. McElroy, A.D., S.Y. Chiu, J.W. Nebgen, A. Aleti, and F.W. Bennett. Loading Functions for Assessment of Water Pollution from Nonpoint Sources. #EPA-600/2-76-151, p. 239. Office of Air, Land and Water Use, Office of Research and Development, U.S. Environmental Protection Agency, Washington, D.C., May 1976.

10. Morel, F., and J. Morgan. A Numerical Method for Computing Equilibria in Aqueous Chemical Systems. *Environmental Science and Technology*, *6*(1): 58-67 (1972).

11. McDuff, R.E., and F.M. Morel. Description and Use of the Chemical Equilibrium Program REDEQL2. Technical Report EQ-73-02. Keck Laboratory of Environmental Engineering Science, California Institute of Technology, Pasadena, California, December 1973 (updated July 1975 by J.J. Morgan).

12. Gordon, J.G. Assessment of the Impact of Resource Recovery on the Environment. #MTR-8033. The MITRE Corporation, Metrek Division, McLean, Virginia, December, 1978.

ENVIRONMENTAL ASSESSMENTS OF WASTE TO FUEL PROCESSES

H. M. Freeman
Fuels Technology Branch
Energy Systems Environmental Control Division
Industrial Environmental Research Laboratory--Cincinnati
Office of Research and Development
U. S. Environmental Protection Agency

ABSTRACT

This paper discusses expected emissions from waste to energy conversion systems. It provides an overview of waste to energy conversion technology, a discussion of relevant Federal environmental standards, and a compilation of the results of environmental assessments of two systems; (1) an RDF combustion system at Ames, IA, and (2) a partial oxidation pyrolysis unit at South Charleston, WV. Data is provided for Criteria Pollutants and for various trace elements.

INTRODUCTION

For communities faced with costly municipal solid waste disposal problems and for individuals within those communities faced with constantly increasing costs for heat and power, the idea of utilizing the waste stream to supplement conventional energy supplies is becoming increasingly attractive. The possibility of converting solid waste, a potential environmental pollutant, into a useful and valuable energy source is appealing. There are on the scene today several rather well developed systems for converting wastes to energy, and within the next five years it is expected that many other presently undemonstrated technical options will become available. In the next decade, the conversion of waste to energy could become accepted as a waste disposal option in many of the nation's cities and could represent a small but very real supplement to conventional energy production sources.

Conversion of solid waste to energy offers a means of lessening one very real environmental problem, solid waste disposal. However, since conversion units involve fuel combustion, they are also sources of air pollution. These air pollution problems must be recognized and addressed by anyone considering adopting one of these systems. This paper discusses what types of air pollution one might expect from these systems, the results of several recent environmental assessments, and what environmental standards one must meet in operating the plants.

OVERVIEW OF WASTE TO ENERGY CONVERSION TECHNOLOGY

The various thermal processes for recovering energy from solid wastes can be categorized into three major areas.

Mass Burning Incinerators with Heat Recovery

The waste is fired in a processed or unprocessed form in a boiler lined with water filled tubes that transform the released heat into steam. Such plants are presently in operation in Nashville, Saugus, MA., Chicago, and Braintree, MA.

Combined Firing Systems

The waste is first processed to remove non-combustibles and to reduce the particles to common sizes, and then is fired as a supplemental fuel with coal, oil, or natural gas in a modified industrial or utility boiler. The processed refuse is sometimes referred to as a refuse derived fuel (RDF). Combined firing plants are operating in Ames, IA, Chicago and Milwaukee. An earlier demonstration operation was conducted by the Environmental Protection Agency (EPA) at a Union Electric plant in St. Louis.

Pyrolysis Processes

The solid waste is converted thermochemically in an oxygen starved environment into a liquid, gaseous, or solid fuel product. These fuels are storable and transportable products which can be utilized as either primary or supplemental fuels. There are presently no commercial scale pyrolysis plants in the country. A demonstration scale plant is being operated by the Union Carbide Company in South Charleston, WV.

AIR POLLUTION

Waste to energy conversion systems produce as emissions particulate matter, sulfur oxides, nitrogen oxides, hydrogen chloride, hydrocarbons, carbon dioxide, carbon monoxide, and trace elements. Table 1 lists some early data on emission factors for pollutants from controlled waste combustion operations. Emission factors are used to calculate expected emissions from controlled facilities.

Of these pollutants, particulate matter is the most significant in terms of present environmental regulations. Particulate matter is any material except uncombined water in the form of solid or liquid in the gas stream. It consists of fly ash, dust, aerosols (microscopic sized particles) and mists. Emission rates for particulate matter vary widely depending on moisture and ash content of the fuel, unit design, and combustion parameters. However, uncontrolled rates of from 15 to 24 pounds of particulate per ton of refuse fired are generally produced by waterwall incinerators.

Gaseous emissions from waste-to-energy conversion are not presently viewed as a significant environmental problem. Refuse is a low sulfur fuel, averaging only about 0.3 percent sulfur (as compared to 1 to 3 percent for coal). Consequently, SO_2 production is minimal. Significant nitrogen oxides formation usually occurs at temperatures of above 2000°F. Most waterwall incinerators operate at much lower temperatures. Although combustion temperatures are higher in RDF cofiring situations, the marginal contribution of the RDF to NO_x production appears to be minimal. Unburned hydrocarbons and carbon monoxide are usually present in significant amounts only if proper combustion is not taking place. Proper flame turbulance, ample combustion times and sufficient temperatures will reduce the quantities of CO and hydrocarbons to negligible levels.

Chlorine is usually present in solid wastes as inorganic chlorides in polymers. It is estimated that chlorine is present in municipal wastes in concentrations of up to .5 percent by weight. The combustion of this chlorine, expecially of the chlorine contained in polymers, causes HCl in the stacks. One of the common findings in assessments run at solid waste combustion facilities has been the presence of HCl in greater quantities than in the stacks of coal-fired units.

Although data are extremely limited concerning trace element emissions from waste-to-energy conversion systems, several studies have indicated that refuse combustion can produce airborne pollutants not produced by conventional fuel combustion. The EPA evaluation of the St. Louis RDF plant indicated that such potentially hazardous substances as beryllium, cadmium, mercury, copper, and lead were present in higher concentrations in the emission streams from coal plus RDF combustion than they were in emissions from coal only combustion. On the other hand, data from another RDF plant at Ames, IA (discussed later) showed that trace element emissions from coal + RDF combustion were generally less than trace element emissions from coal only combustion. A National Science Foundation study found that in two metropolitan areas, refuse incineration could account for major portions of zinc, cadmium, and antimony observed on airborne particles. The study also suggested that refuse incineration was a large source of another toxic element, vapor phase mercury.

WATER POLLUTION; SOLID RESIDUALS

Since waste-to-energy systems usually use water only for ash quenching and facility clean-up, they are not typically seen as a major source of water pollution. Two exceptions to this general statement are RDF/coal cofiring installations in which water is used to sluice the ash, and pyrolysis systems in which water is used as a scrubbing medium for the product gas.

In the cofiring case, sluice water from the St. Louis demonstration unit was found to exceed state standards for BOD, dissolved oxygen and total dissolved solids and to contain higher concentrations of twelve other pollution parameters than a sluice stream from a coal-only boiler.

In the pyrolysis case, the untreated wastewater stream from these units is expected to have very high concentrations of BOD, COD, phenols, and other organics and will certainly require treatment. Such treatment is included as part of the commercial-scale units presently being developed.

If a waste-to-energy system is discharging into a municipal sewer system, which is the case for most units in operation today, usually only minimal treatment such as setting and p^H adjustment is required. If the effluents were discharged into public waterways, more extensive treatment would be necessary.

Characterization of the solid residuals from waste-to-energy conversion systems has been minimal to date. These residuals are produced as bottom ash and processing rejects, recovered fly ash and, for high temperature slagging incineration and pyrolysis units, an inert slag.

Trace elements such as beryllium, mercury, cadmium, and lead have been reported to be present in the fly ash from coal plus refuse systems. The extent to which trace elements are enriched in the fly ash is not fully understood.

ENVIRONMENTAL STANDARDS

There are in existence Federal environmental standards for major sources of air pollution built or significantly modified since December 1971. Sources built before that time are covered by the environmental regulations of the state in which they are located. The Federal standards are titled the New Stationary Source Performance Standards (NSSPS). The standards require that a facility emit not more than a given amount of certain pollutants based upon existing state-of-the art for relevant control technology.

The pollutants covered by the NSSPS are particulate, NO_x, SO_x hydrocarbons, and carbon monoxide. These substances are commonly referred to as the Criteria Pollutants. The Criteria Pollutants of most interest to designers and operators of waste-to-energy conversion systems are particulate matter, SO_x, and NO_x. The principle sources of hydrocarbons and carbon monoxide emissions are automobiles and petroleum processing operations.

The NSSPS for mass burners addresses only particulates. The NSSPS for fossil fired steam generators, the combustion units for RDF systems include particulate, SO_2 and NO_x. It should be noted here that since no new boilers designed to burn RDF have been put into operation since 1971, the EPA has not yet said that the standards for fossil fuel fired steam generators will apply. However, the Clean Air Act requires that the standards be revised periodically, and the stated standards will be revised in some way to incorporate RDF as a fuel. There are no NSSPS for pyrolysis systems since these systems do not have atmospheric emissions. However, the combustion of the resulting gas could be treated under the "gas" subcategory for the fossil fuel fired steam generator. The existing standards for the various systems are shown in Table 2.

To date no emission standards for trace element emissions from waste to energy systems have been developed. None of the EPA Standards for Hazardous Pollutants* apply to either incinerators, pyrolysis units, or fossil fuel fired boilers. With increasing attention being given by the EPA to toxic substances, more consideration may be given in the future to trace element regulation.

ENVIRONMENTAL ASSESSMENTS

The Industrial Environmental Research Laboratory (IERL), Cincinnati, a part of EPA's R&D program has the responsibility for determining emissions from waste-to-energy conversion systems to insure that control technology development accompanies advances in conversion technology. Listed below are brief discussions of the findings of assessments at two facilities: a slagging pyrolysis plant operated by the Union Carbide Company, at South Charleston, WV; and a utility boiler in Ames, IA in which RDF is used as a fuel. The latter project was conducted in cooperation with the U. S. Department of Energy.

THE UNION CARBIDE PUROX PROCESS

Process Description

Since 1975 the Union Carbide Company has operated a demonstration scale pyrolysis plant (200 tons of solid waste per day) at South Charleston, West Virginia. The plant converts the combustible fraction of solid waste into a gas having a heat value of approximately 1/3 that of natural gas, and converts the non-combustible part of the solid waste into a very dense inert slag.

After particle size reduction and ferrous metal removal, the solid waste is injected into the top of a vertical pyrolysis reactor. Oxygen is injected into the bottom of the reactor at ratio of about 20% by weight of the incoming refuse. The oxygen reacts with char formed from the refuse to generate temperatures of 2500° to 3000°F in the lower zone which converts the non-combustibles into molten residue, and pyrolyzes the refuse in the upper part of the reactor into a gas. The gases are passed through a scrubber and a precipitator prior to being burned as a fuel gas. A diagram of the Purox process is shown in Figure 1.

Environmental Assessment

In November of 1977 the EPA carried out an environmental assessment of the Purox facility and of a package boiler brought to the site to combust the product gas. The boiler, equipped with special burners to burn the Purox gas, had a rating of 30×10^6 Btu/hr. Emissions from the combustion of Purox gas were compared to emissions from burning natural gas. The results are shown in Tables 3 and 4.

The conclusions of the air emissions assessment were:

1. The Purox system successfully demonstrates the production of a combustible fuel gas from solid waste.
2. Of the Criteria Pollutants that result from combustion of the Purox gas, only NO_x and particulate show a significant increase at the outlet of the boiler.
3. The NO_x emissions from the Purox gas if they were present in the larger size boiler covered by the NSSPS would exceed the NO_x standard.
4. Particulate emissions are well below the Federal standard.
5. SO_2 levels do not appear to be a problem.

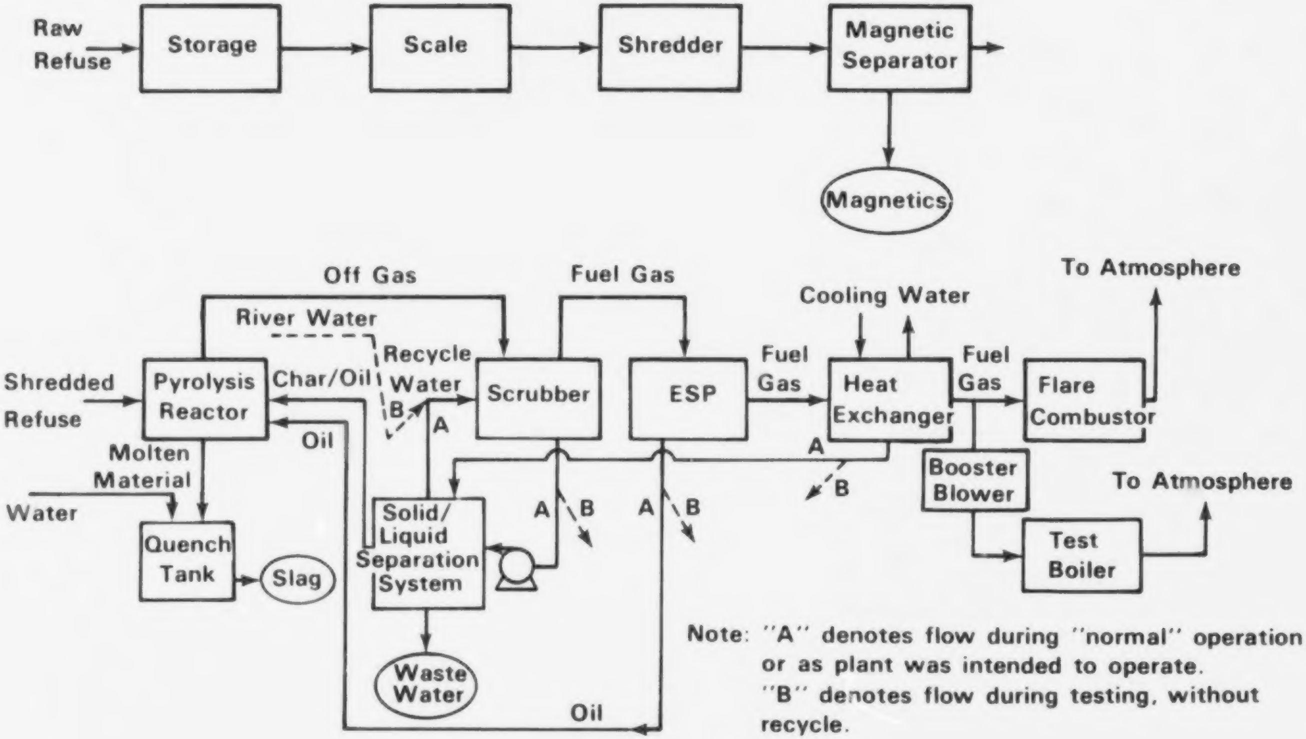
Samples on input river water and effluent scrubber water were taken each test day. Additionally, during one day grab samples were taken before and after the Unox water treatment system which is part of the Purox process. Results of the analyses of the samples for general water quality parameters were much higher in the scrubber effluent than in the inlet water. The Unox system did improve most of the general water quality parameters with the exception of Total Suspended Sediment and Dissolved Oxygen. However, neither TSS nor BOD would meet secondary treatment criteria of 30 mg/liter. Also, even though the Unox system did decrease the phenol level from about 90 mg/liter to .7 mg/liter this may not be sufficient to meet stringent water quality criteria for phenols that may be as low as .001 mg/liter.

At the findings and conclusions of the assessment are included in a paper "Air Emissions Assessment - Union Carbide Process," presented at the 71st Annual Meeting of the Air Pollution Control Association, Houston, Texas, June 26, 1978, and will be included in an EPA report, "Environmental Assessment of the Union Carbide Purox Process," in process for publication by IERL-Ci.

AMES SOLID WASTE RECOVERY SYSTEM

Since 1975 the City of Ames, Iowa, has operated a system for recovering materials and energy from solid waste. The system consists of a processing plant capable of processing 150 tons/day of solid waste, a storage facility, and an existing municipal power plant. Solid waste is shredded and processed to remove non-combustibles. The remaining combustible fraction (RDF) is fired in a stoker fired boiler at the average rate of 4-5 tons per hour (50% input on a heat energy input basis). The two boilers used to burn RDF are rated at 95,000 and 125,000 pounds of steam per hour. Mechanical dust collectors are the only type of air pollution control equipment installed on the stoker fired units.

During the summer of 1976 an environmental assessment of the Ames plant was carried out by investigators under an EPA grant. During the assessment the boiler load was set at 60, 80, or 100% and the percent RDF varied from 0 to 50% of the feed on a heat input basis. Sampling, physical characterization, and chemical element analysis were performed on input fuels, ash, and a compilation of the findings of the


Raw Refuse
Storage
Scale
Shredder
Magnetic Separator
Magnetics
Off Gas
Fuel Gas
To Atmosphere
Cooling Water
River Water
Recycle Water
Shredded Refuse
Pyrolysis Reactor
Char/Oil
B
A
Scrubber
ESP
Fuel Gas
Heat Exchanger
Fuel Gas
Flare Combustor
Oil
Molten Material
Water
Quench Tank
Slag
Solid/ Liquid Separation System
A
B
A
B
A
B
Booster Blower
To Atmosphere
Test Boiler
Waste Water
Oil

Note: "A" denotes flow during "normal" operation, or as plant was intended to operate.
"B" denotes flow during testing, without recycle.

Figure 1. Flow diagram for Purox® process.

effect on stack pollutants of using 20% and 50% RDF is shown in Table 6.

The effects on selected Criterial Pollutants of firing RDF as a fuel are shown in Table 7.

The environmental assessment at Ames found that the particulate emissions decreased when RDF was added to the feed. This is contrary to earlier findings. It should be noted, though, that the particular coal used for these tests had an ash content of 20% versus an ash content of 17% for the RDF. NO_x and SO_x emissions both decreased as the percent RDF was increased. Interestingly, with the exception of lead and copper, all of the trace metals analyzed appeared in lower concentrations in the fly ash resulting from the coal plus RDF than in the coal only fly ash.

The complete results of the environmental assessment at Ames is contained in the report "Evaluation of the Ames Solid Waste Recovery System" - EPA Grant #80393, which is now under review for publication by EPA's Industrial Environmental Research Laboratory, Cincinnati.

SUMMARY

While waste to energy conversion offers an attractive alternative to traditional solid waste disposal as a means of managing wastes, there are still environmental questions which must be addressed. This paper has discussed some of these questions. The EPA's assessment programs such as the ones discussed herein will provide answers to these questions and insure that waste to energy conversion will indeed fulfill its promise as a positive approach to environmental improvement.

*EPA's Standards for Hazardous Pollutants apply to specific pollutants which have been found to present clear threats to the public health. The present list includes asbestos, benzene, beryllium, mercury, and vinyl chloride.

TABLE 1: POUNDS OF POLLUTANTS DISCHARGED PER TON OF WASTE COMBUSTED

	Pounds
Particulates	1.5
Sulfur oxides	1.5
Carbon monoxide	35.0
Hydrocarbons	1.5
Nitrogen oxides	2.0
Hydrogen chloride (est.)	0.6

Source: Compilation of Air Pollutant Emission Factors
U. S. EPA, Office of Air Programs, AP-42, 1971

TABLE 2: STANDARDS OF PERFORMANCE FOR NEW STATIONARY SOURCES

Source Category	Affected Facility	Pollutant	Emission Level
Subpart D - Fossil-Fuel Fired Steam Generators			
	Coal, coal/wood residue fired boilers >250 million Btu/hr	Particulate Opacity SO_2 NO_x	0.10 lb/10^6 Btu 20%: 40% 2 min/hr 1.2 lb/10^6 Btu 0.7 lb/10^6 Btu
	Gas, gas/wood residue fired boilers >250 million Btu/hr	Particulate Opacity SO_2 NO_x	0.10 lb/10^6 Btu 20%: 40% 2 min/hr 0.20 lb/10^6 Btu
Subpart E - Incinerators			
	Incinerators >50 tons/day	Particulate	0.08 gr/dscf corrected to 12% CO_2

TABLE 3: UNION CARBIDE PUROX ENVIRONMENTAL ASSESSMENT

Boiler Flue Gas Particulate and Opacity Data

	Fuel Type	
	Natural Gas	Purox Gas
Flue Gas Flow Rate (d Nm^3/min)	93-108	76-80
Particulate Concentration (mg/d Nm^3) a/	0.94-2.40	4.07-14.28
Opacity (%)b/	5	5

---

a/ Includes only "front half" particulate weights filter catch plus acetone rinse of probe) from HVSS (high volume sampling system) sampling train consistent with EPA Method 5.

b/ Average of two, one-hour observations.

TABLE 4: UNION CARBIDE PUROX ASSESSMENT

Boiler Flue Gas Constituents

	Fuel Type	
Flue Gas Constituents	Natural Gas	Purox Gas
H_2O (%)	17.9-19.7	13-14.3
CO_2 (%)	10.3-11.0	20.5-20.7
O_2 (%)	2.5-4.4	1.1- 5.6
CO (ppm)	0-15	0-289
HC (ppm)	0-2.4	0
NO_x(ppm)	70-110	203-504
SO_2(ppm)	1-1.4	68-113

TABLE 5. WATER QUALITY ANALYSES

Test	pH		Oil & Grease (mg/1)		TSS[a/] (mg/1)		Purox Scrubber Influent & Effluent COD (mg/1)		Purox Scrubber Influent & Effluent COD (mg/1)		DO (ppm)		Phenols (mg/1)		Turbidity (JTUs)[c/]		River Water Flowrate to Scrubber	
No.	RW	SW	RW	SW	RW	SW	RW	SW	RW	SW	RW	SW	RW	SW	RW	SW	(1/min)	(CPM)
4	7.7	5.2	<1	50	11.0	31.5	10	>4,080	35	10,900	6.5	2.4	0.3	118	35	280	Not read	
5	7.6	5.0	2.0	52	13.0	112	2	4,200	15	10,850	3.7	2.8	0.4	118	35	200	337	89
6	7.2	4.9	<1	77	16.0	88.0	1	4.200	29	11,480	6.8	3.4	0.1	128	<25	130	329	87
7	7.5	4.8	<1	79	17.0	92.5	3	4,950	33	13,150	7.1	3.7	0.4	131	<25	110	333	88
									Unox Grab Samples								Flowrate through Unox System	
RW	7.5		5.4		12.5		<1		3.9		5.3		0.08		<25		12.5	3.3
Unox in[b,d/]		4.7		29.8		63.0		3,600		7.190		3.8		91.2		290	3.4	0.9
Unox out[b/]		6.9		2.6		60.0		48		569		3.9		0.74		150	15.9	4.2

RW = River water (scrubber influent)
SW = Scrubber water (scrubber effluent)

a/ Scrubber water effluent was filtered prior to analysis since it contained solid material that should have been removed from the effluent by the process if it were operating as intended by UCC. The effluent as sampled here is a once-through system and not recycled sample as would be the case when the process is operating "normally."

b/ "Unox-in" was a sample of the Purox effluent when water was being recycled. This effluent was diluted with 4 to 6 parts river water prior to treatment in the Unox system.

c/ JTU - Jackson Turbidity Units.

d/ "Unox-in" samples were, according to UCC, not representative samples of recycled water since the recycle system had not attained equilibrium.

TABLE 6. UNCONTROLLED EMISSIONS OF SELECTED TRACE ELEMENTS IN FLY ASH AT AMES, IOWA, RDF PLANT (AVERAGE VALUES, μg/g)

Element	Coal Only	Coal Plus 20% RDF	Coal Plus 50% RDF
Aluminum	86,149	65,137	55,228
Chromium	183	179	143
Copper	153	472	379
Iron	86,914	22,133	22,133
Lead	6,733	31,684	22,815
Selenium	46	87	

TABLE 7: UNCONTROLLED EMISSIONS OF CRITERIA POLLUTANTS FROM THE AMES, IOWA, RDF PLANT

	Coal Only	Coal Plus 20% RDF	Coal Plus 50% RDF
Particulate			
mg/Nm^3	9679	4851	7597
gr/dScf	4.002	2.006	3.141
Gases (ppm) No$_x$	94	83	60
SO$_2$	2080	1539	1494

THE OCCURRENCE OF LEAD IN MUNICIPAL SOLID WASTE

David F. Lewis and Ada Salas
York Research Corporation
One Research Drive
Stamford, Connecticut 06906

ABSTRACT

The recycling of the waste products produced by our society has provided some exciting solutions to problems associated with solid waste disposal and energy production. In this regard, a number of municipal solid waste (MSW) treatment systems have been commercialized. The end product of these processes is a cellulose based refuse derived fuel (RDF). Combustion of RDF in coal fired utilities can provide useful energy and it is a particularly attractive fuel because of its low sulfur content. However, some components of MSW may contain lead and other toxic metals and these may enter the RDF process stream and become part of the fuel. Lead containing materials are present in both the combustible and non-combustible fractions of MSW. Efficient methods are available for the separation of these combustible and non-combustible fractions. However, the use of lead based pigments in colored papers and printing inks and lead based stabilizers in plastics can result in significant quantities of lead being intimately bound to various combustible materials from which RDF is derived.

INTRODUCTION

Municipal solid waste (MWS) is generated in the United States at a rate of approximately 4 lb per person per day and is growing at a rate of about 1.5% per year. The management of this volume of "trash" has become a major problem for communities, particularly from the point of view of disposal. Solutions to the problem have to satisfy both economic and environmental requirements. Thus we have seen well worn alternatives such as incineration and landfill come under close scrutiny. The results have been revealing and damaging.

At the same time that these problems have been widely appreciated, we have also been brought face to face with a growing energy problem. Not that this nation's fuel resources are low or in danger of being exhausted - they certainly aren't. The problem is more one of economics related to the rapidly increasing cost of using environmentally acceptable fuels (e.g. oil, gas) or using fuels in an environmentally acceptable manner (e.g. coal).

However, there have been active minds among us who have seen that the problems of "trash" and energy may have a common solution, if not in total at least solution in part. This solution is the recovery of material resources and energy from municipal solid waste. Not that the ideas or processes involved are novel, many of them are not. Rather it is the sum of the parts or the scale of operations that is new. Thus municipal solid waste is divided into combustible and non-combustible fractions. From the non-combustible fraction, metals and glass are recovered, and from the combustible fraction is made refuse derived fuel (RDF). This RDF is a solid, cellulose based fuel that can be conveniently used as a supplemental fuel for coal fired utility boilers. Moreover it is attractive because it has a sulfur content of less than 0.5% and in the appropriate proportions could be co-fired with high sulfur eastern coals without violation of sulfur dioxide emission codes.

However, we must now look a little into the future where we may face regulations governing the emission of species such as lead, mercury, cadmium, zinc, arsenic, beryllium and other volatile toxic metals. Does refuse derived fuel contain significant amounts of any of these materials? How much is there, how does it get there, can it be removed, will the combustion of that RDF violate emission requirements? These are the questions, now is the time to begin generating the answers.

The metal in which we are principally interested is lead, but during the course of the investigation on which we have recently embarked we are also maintaining a concern about nickel, arsenic and beryllium. Our study is supported by the EPA and is designed to determine how lead is accumulated in RDF, how much and in what compound forms is the lead present, what happens to the lead when the RDF is combusted and how can the lead be removed from the RDF and be prevented from reaching the environment. For the purposes of the following discussion we shall be primarily concerned with the problems of accumulation of lead in RDF. However, it is pertinent to begin by considering the effect of burning a fuel containing lead.

EMISSION OF LEAD

There is little doubt that the combustion of materials containing volatile metals, and lead in particular, does lead to metal emission in the effluent gas stream. Several studies have shown that approximately 2/3 of the lead present in coals can be expected to be released with the fly ash and 1/3 remains in the bottom ash. Of course, methods for the removal of particulates from flue gases have been well developed, but the volatile metals present a particular problem. Various workers have shown that lead emitted in flue gas is not equally distributed among the various particles in that gas stream. Rather it is associated with the finest particles. This phenomenum arises because of the volatility of lead and lead compounds. They are thus present in the vapor phase in portions of the combustion zone where the fly ash is formed. Only when the flue gas cools down is the lead desposited on the solid phase. Moreover, because this deposition is a surface phenomenum, the lead becomes concentrated on those particles having the highest ratio of surface area to mass, i.e. small particles. Data has shown that more than 75% of lead emitted from a certain combustion process was associated with particles less than 2 micron in size despite the fact that these particles accounted for less than 10% of the total particles emitted.

There is a low efficiency of removal of small particles, i.e. <1 micron, from a flue gas stream. In addition, these small particles are the very ones which are inhaled and retained in the lungs. Therefore the presence of lead in fuel may present a particular hazard to our health and is a problem necessitating urgent investigation.

Let us now turn our attention to RDF and consider the pathways by which lead arrives in the municipal solid waste from which these refuse derived fuels are derived.

COMPOSITION OF MUNICIPAL SOLID WASTE

The first prerequisite for this investigation is to aquire an understanding of the composition of MSW. One quickly realizes that MSW is a heterogeneous assortment of materials, and its composition will vary on a seasonal basis and according to location in both the narrow and wide sense. The values that are indicated in Table 1 are derived from a number of sources, but give a realistic indication of MSW make-up on a dry weight basis. It should be appreciated that MSW is never received or handled dry and that its moisture content could be in the range 5-30% depending on composition and climatic conditions. Furthermore, the greater part of the moisture will be associated with the cellulose, the putrescible food waste and yard waste portion of the combustible fraction.

The combustible fraction of MSW is composed of paper, plastics, wood, textiles, putrescible food and yard waste, leather and rubber. Although this accounts for 55-70% of MSW, a considerable portion does not enter the fuel process stream of most RDF manufacturing operations. This is a

Table 1 COMPOSITION OF MUNICIPAL SOLID WASTE ON DRY WEIGHT BASIS

Product	Typical Content*, percent	Range of Content†, percent
Paper	51.7	35 - 60
Glass	10.5	4 - 23
Fine glass, dirt, ceramics	10.0	9 - 20
Ferrous metal	7.6	5 - 13
Plastics	5.0	2 - 8
Putrescibles	4.4	2 - 25
Corrugated board	3.5	3 - 25
Wood	2.6	0.4 - 8
Fabrics	1.8	1 - 9
Aluminum	0.1	0.6 - 3
Leather and Rubber	0.7	0.4 - 5
Heavy non-ferrous metals	0.2	0.2 - 0.6
Miscellaneous	0.9	0.5 - 15

*Source: Waste Age, September 1978, p. 54. † Max. and min. values from literature data.

result of the physical phenomena that the various separation processes employ, as well as the physical characteristics of some of the components of MSW. Thus rubber tires are extremely difficult to handle and are usually manually removed from the process stream at an early stage. One of the common separation techniques used in RDF processing is air classification. This procedure separates materials according to their mass per unit surface area and therefore in most, but not all, of the MSW resource recovery processes in operation, the RDF is derived primarily from the light combustible fraction, i.e. paper, plastic and textiles. In these instances it is a good rule of thumb to say that 2 tons of MSW will produce 1 ton of RDF.

LEAD CONTAINING MATERIALS IN MUNICIPAL SOLID WASTE

Now that we have an appreciation for the composition of MSW let us consider the uses of lead and find out in what components of MSW can lead be found.

Lead is used in the United States at a rate of about 1.5 million tons per year. Over the last 10 years the consumption of lead has risen only about 20%. This growth may be largely offset by the phase out of lead containing gasoline additives as they account for about 18% of lead used Another 72% of lead is used in metal products such as ammunition, alloys, cable sheathing, tubes and pipes, lead sheet and foil, type metal, storage batteries, lead plating, solder, and ballast. Lead is used in the making of both white and colored pigments, and this accounts for about 8% of lead consumption. The remaining 2% is spread over numerous products.

We now see from Table 2 how lead may occur in each of the components of MSW that we have identified earlier. For ease of use some of these components of MSW have been sub-classified. There is also included in Table 2 an indication of whether the occurrence of lead in these items is common or rare. We cannot be totally objective about this designation, but when taken in conjunction with the proportion of that item in MSW it does allow one to spotlight areas of concern.

The data contained in Table 2 reveals some disturbing information - considerable portions of the combustible fraction of MSW contain lead. There is a lack of data giving information as to the lead content of all the various combustible and non-combustible fractions of MSW and work in this area is urgently required. However, some investigators have determined that the overall lead content of MSW may be in the range 1000-5000 ppm and that lead may be present at up to 350 ppm in the light combustible fraction. These figures would indicate that the non-combustible fraction of MSW contains appreciable quantities of lead. Nevertheless, because the derivation of RDF from MSW involves separation of the combustible and non-combustible fractions, it is worthwhile to consider these separation procedures.

Table 2 OCCURRENCE OF LEAD IN MUNICIPAL SOLID WASTE

Fraction	Component/ Subcomponent	Form of Lead	Occurrence
Non-Combustible:			
	Metal:		
	Ferrous	Alloys	Rare
		Solder	Common,High
		Galvanizing	Rare
		Paints/Primers	Common
	Aluminum		Rare
	Non-Ferrous	Alloys	Common,High
		Cable Sheathing	Common,High
		Collapsible Tube	Common,High
		Foil and Sheet	Common,High
		Pipes	Common,High
		Solder	Common,High
		Batteries	Common,High
		Ballast	Common,High
	Glass:	Crystal Glass	Common,High
	Ceramics:	Glazes	Common,High
		Enamels	Common,High
Heavy Combustible:			
	Putrescibles:		
	Food Waste	Hopefully none	Hopefully rare
	Yard Waste	Pesticides	Rare
		Fungicides	Rare
		Horticultural caulk	Common
	Wood:	Paints/Primers	Common
	Leather:		Rare
	Rubber:	Stabilizers	Rare
Light Combustibles:			
	Paper:		
	Newsprint		Common,Low
	Kraft Paper		Common,Low
	Corrugated board		Common,Low
	Paperboard	Pigments	Common,High
	Magazines	Pigments/Glazes	Common,High
	Colored wrapping paper	Pigments	Common,High
	Plastics:	Stabilizers/Pigments	Common,High
	Fabrics:		Rare

PROCESSING OF MUNICIPAL SOLID WASTE

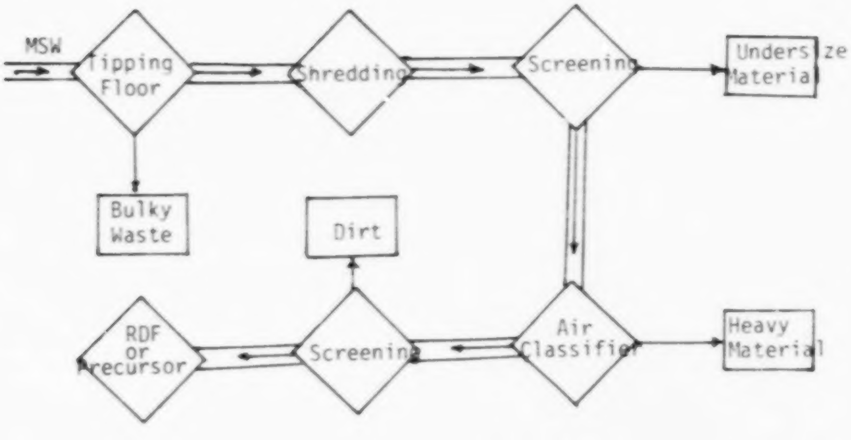
Many schemes for the processing of MSW have been devised and commercialized. It is beyond the scope of this paper to consider each of these processes in detail. However, since many of the processes involve similar steps, the generalized scheme depicted in Figure 1 will serve to illuminate several points.

The basic steps of the process are as follows. MSW is received on the tipping floor and oversize bulky waste, e.g. refrigerators, mattresses, etc. are removed by hand. The material is then sent to a shredder where it is reduced to a 4"-6" size and from there it goes to a screen where undersize material is removed. The undersize material is likely to be primarily composed on non-combustibles such as glass and metal although a certain amount of food and yard wastes are also removed. Oversized material is then fed to an air classifier which is designed to pull off the light components such as paper, cardboard, rags, plastic, etc. Air classification may be performed in more than one step, but the result should be a process stream essentially free from metal, glass and ceramics. A further screening of the light process stream may then be performed in order to remove dirt and powdered glass that remains adhered to the light fraction. The efficiency of this final dirt removal process depends to a large extent upon the moisture content of the process stream, but if the material is dry, an excellent separation may be accomplished.

The remaining process stream contains the light combustible fraction of MSW and is composed primarily of paper and plastics with lesser amounts of rags, wood, leather and rubber. This then is the process stream that comprises the RDF or the RDF precursor. According to the particular RDF involved, there may be further size reduction or chemical treatment or compaction. With good separation

FIGURE 1

PROCESS STEPS FOR MSW HANDLING



Procedures, the amount of non-combustible materials remaining in the light combustible fraction should be considerably less than 5% by weight and will be primarily composed of metals in the form of paper clips, staples and aluminum foil together with ground glass, ceramics and dirt. Since most of the lead in the non-combustible fraction of MSW is likely to be in the form of bulky items such as pipe, cable sheathing and storage batteries, it is felt that adherence to good separation procedures will result in the removal of more than 95% of the lead contained in the non-combustible fraction. However, these figures should be subjected to experimental verification.

LEAD IN THE COMBUSTIBLE FRACTION OF MUNICIPAL SOLID WASTE

The literature contains data indicating that the light combustible fraction of MSW contains up to 350 ppm of lead. This is lead that is intimately associated with paper and plastics and cannot be removed by procedures required for the separation of non-combustible components of MSW. Since it is suspected that the removal of the lead in the non-combustible materials is highly efficient, we anticipate that the lead used in the paper, printing and plastic fabrication industries will be of prime importance with respect to lead content of RDF. The figure of 350 ppm lead in RDF represents a value at least one order of magnitude higher than that for coal and oil. This gap would about double when the lead content of the various fuels is calculated on a Btu basis. Once again it should be stated that the 350 ppm figure must be subjected to detailed investigation and verification.

The data presented in Table 3 has been gathered to provide an appreciation of the lead content of various components of the combustible fraction of MSW.

It must be restated that the values for the composition of the combustible fraction of MSW represent those for a single sample and the composition of a given sample may vary considerably from those in the table. However, it can be clearly seen that the principal contributors to lead in RDF are the pigments used in the printing of colored papers and the stabilizers used in plastics, and of these it it is the former that is the major problem.

Table 3 COMPOSITION AND LEAD CONTENT OF COMBUSTIBLE FRACTION OF MSW IN THE U.S.

Component	Composition, percent	Lead component	Lead Content, ppm
Corrugated board	13.4		6 - 50
Newspapers	9.0		9 - 45
Paperboard	6.8	Pigments	40 - 500
Paper packaging	6.3	Pigments	5 - 10,000
Office paper	6.1		10
Magazines, books	3.8	Pigments, glazes	10 - 3500
Tissue paper, towels	2.6		
Paper plates, cups	0.7		
Other	1.5		
Yard Waste	17.8	Pesticides, fungicides	
Food Waste	16.8		
Plastic	5.2	Stabilizers, pigments	10 - 1000
Wood	4.6	Paints, primers	
Leather, rubber	3.4	Stabilizers	
Textiles	2.0		

Lead chromates and oxides are widely used in red, orange and yellow pigments used for the printing of colored papers, while metallic soaps such as lead naphthenate are incorporated to accelerate drying formulations applied as paper finishes such as glazes and sizings. The plastics industry uses lead sulfate and a variety of organo lead compounds as additives to polyethylene, polystyrene and polyvinylchloride in order to promote stability. It is these plastics that comprise the bulk of the plastic fraction of MSW.

One further point worth noting concerns the amount of lead in cardboard and newsprint. Both of these materials might commonly be fabricated by using recycled paper. However, as the recycled paper will contain some color printed material, it follows that cardboard and newsprint derived from that recycled paper will be contaminated with lead.

REMOVAL OF LEAD FROM REFUSE DERIVED FUEL

The combustible and non-combustible fractions of MSW may be efficiently separated, and from the data that we have gathered it seems likely that the major contributors to lead in RDF are those components of the combustible fraction that have lead compounds intimately bound to them.

It is certain that much more data is needed concerning the lead content of MSW and RDF. In particular we need to determine precisely how much of the lead in the combustible fraction of MSW comes from the residual non-combustible fraction and how much is present as a result of lead intimately bound to the combustible materials. We also must determine whether the combustion of RDF containing, let us say, 350 ppm lead is likely to lead to a violation of future emission statutes.

Although we should not be presumptuous, let us consider the removal of lead from the conbustible fraction of MSW, i.e. the fraction from which RDF is derived. Separation techniques might involve a chemical and/or a physical process. Chemical separation is not east to envision without wetting of the RDF and the use of a subsequent drying step. If one were to use an aqueous based system the cost of drying alone can be estimated as being considerably in excess of $6 per ton of RDF. For a fuel whose worth may be about $20 per ton, this clearly represents a serious economic drawback.

Physical separation would appear more attractive. Indeed there are several appropriate methods for separation of the plastics from paper and these should be given consideration. However, because of the use of lead based pigments in colored papers we may be faced with a problem that requires separation of various types of paper. Processes that could accomplish this on a commercial scale are not visible on the horizon.

The use of additives to convert the lead in RDF to non-volatile form during the combustion process is an interesting concept, but again a viable system is not presently known.

Perhaps the best way to remove lead from the combustible fraction of MSW would be to ban its use in pigments used for color printing. This is unlikely to be popular with those sections of industry procuding lead based pigment, nor perhaps with those people using them. However, a precedent has been set by the voluntary restriction of the use of lead based pigments in childrens magazines and comics. Perfectly good and usable lead free pigments are available to the printing industry. Manufacturers are unlikely to assume responsibility for removing lead from their products and they have a strong case. However, in this respect, one can see how astute planning for a national energy policy can be beneficial to society as a whole. Restricting the use of lead in combustible materials likely to end up in municipal solid waste may be a small segment of an overall energy plan, but if we are to decide that our best interests are to be served by recycling and the efficient use of energy then let us resolve to remove trouble at the root and not wait to be confronted with a problem whose solution is technically difficult and economically unattractive.

Funding for this work was provided by U.S. Environmental Protection Agency, Cincinnati, Ohio 45268 under Contract No. 69-03-2742.

START-UP AND OPERATION OF THE LANDFILL GAS TREATMENT PLANT AT MOUNTAIN VIEW

M. J. BLANCHET
PACIFIC GAS AND ELECTRIC COMPANY
SAN FRANCISCO, CA 94106

Abstract

The Mountain View landfill gas treatment plant is a cooperative project involving the City of Mountain View, the Environmental Protection Agency, and the Pacific Gas and Electric Company. Designed to process landfill gas at the rate of 1 MMSCFD,* the plant consists of a compression step followed by adsorption of water, carbon dioxide, and other impurities on a desiccant, activated carbon, and molecular sieves.

Since its completion in May, 1978, the plant has been in sporadic operation, accumulating approximately 230 hours of run time. Following the resolution of mechanical problems in the vacuum cylinder of the compressor and a capacity shortfall due to moisture adsorption by the molecular sieves, a 30-hour test run at design capacity of 1 MMSCFD was made. During this run, treated gas composition averaged 98% methane.

Introduction

Generation of methane gas, a by-product of municipal waste decomposition in landfills, has been viewed historically as a problem. In some of the larger landfills in the U. S., it has been necessary to collect and flare the gas to prevent its migration into adjacent properties where it could form explosive mixtures.

In California, the recovery of landfill gas was initiated by the Sanitation District of Los Angeles County at its Parlos Verdes landfill in 1971. Eighteen wells were constructed to prevent gas migration into adjacent residential properties. The gas thus collected was flared.

The rapid escalation of energy prices in 1973 caused the potential of landfill gas as a source of energy to be recognized, and a successful test program to establish steady-state gas composition and withdrawal rate was developed for the Palos Verdes site.

In October of 1973, NRG Nufuel, now Reserve Synthetic Fuels, Inc., and the Sanitation District entered into a contract to produce and purify landfill gas at the Palos Verdes site for a minimum of five years. A facility to process about 2 MMSCFD of landfill gas was built in the summer of 1975. (1) Since January of 1977, this facility has operated steadily. The pipeline quality gas thus produced is injected into Southern California Gas Company's distribution grid. Currently, Reserve has under construction, at the Operating Industries landfill in Monterey Park, a plant to process 8 MMSCFD of raw gas.

---

*1 MMSCFD = one million standard cubic feet per day.

Also in the Los Angeles area, the Department of Water and Power of the City of Los Angeles, as an outgrowth of its gas-migration control program at the Sheldon-Arletta Landfill, successfully demonstrated the feasibility of generating electricity from landfill gas. An internal combustion engine-generator set was started in April 1974 and ran until February 1975.(2) Since then, the department has designed and is currently building a system to compress, dehydrate and pipe the full production of the Sheldon-Arletta site to its Valley Steam power plant.

Other projects of interest in Southern California are Southwestern Portland Cement's low-btu facility in Azusa, the Wilmington low-btu facility currently undergoing shakedown, and the Industry Hills methane recovery facility which is presently being started up.

PGandE's Activities

Encouraged by the success of the programs at Palos Verdes and Sheldon-Arletta, PGandE surveyed 32 landfills in the San Francisco Bay Area as potential producers of gas. Fourteen of these sites were found to have the potential to produce a combined total of 21 MMSCFD of 450 Btu/SCF* gas, equivalent to 1600 barrels of oil per day, or the average gas requirements of about 41,000 homes. (3) The Mountain View landfill, operated for the City of Mountain View by Easley and Brassy Corporation, showed the greatest promise for an initial demonstration project.

In the summer of 1974, PGandE, the City of Mountain View, and the Environmental Protection Agency (EPA) embarked on a program to investigate the feasibility of recovery of methane from existing landfills using the Mountain View site. The Mountain View site was of interest to EPA because, unlike the Southern California projects, it is a shallow landfill with an average depth of 40 feet as compared to about 150 feet for those in Southern California. Thus, it is more representative of fills throughout the U.S.

This program was completed late in 1976 and reports detailing the findings of this effort were prepared by PGandE and the City of Mountain View. (4,5) Based on the evaluation contained in the PGandE report, it was decided to proceed with a demonstration project at Mountain View to be jointly funded by PGandE and EPA.

Process Description

A process flow diagram is shown in Figure 1. Raw landfill gas at the rate of 1 MMSCFD is extracted from 30 acres with eighteen wells and compressed to 150 psig in two stages. Inter-stage cooling with an air-cooled condenser produces water which is returned to the landfill at the rate of 0.3 GPM. From the knockout pot where water/gas separation takes place, saturated gas flows upward in a cylindrical adsorber where water vapor, carbon dioxide and other impurities are adsorbed on alumina gel, activated carbon, and molecular sieves. Treatment is done sequentially in three towers, with one tower on stream while the other two are being regenerated. Regeneration involves blow-down to atmospheric pressure followed by the application of a vacuum. During a portion of the blow-down cycle to atmospheric pressure, gas flows to the surge drum from which it is

---

*Btu/SCF = British Thermal Unit per Standard Cubic Foot

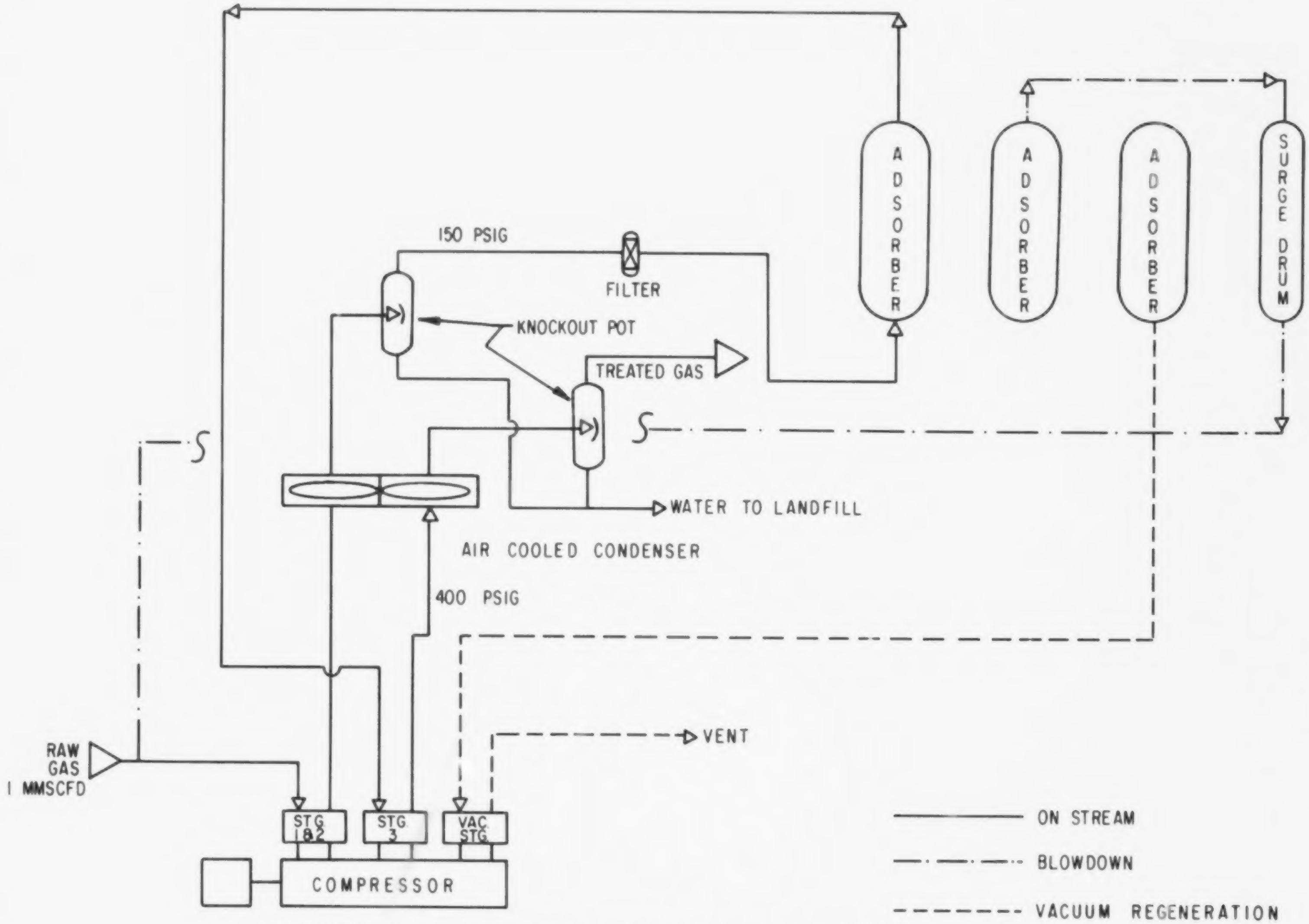

150 PSIG
FILTER
KNOCKOUT POT
TREATED GAS
WATER TO LANDFILL
AIR COOLED CONDENSER
400 PSIG
ADSORBER
ADSORBER
ADSORBER
SURGE DRUM
RAW GAS 1 MMSCFD
VENT
STG 1&2
STG 3
VAC STG
COMPRESSOR
ON STREAM
BLOWDOWN
VACUUM REGENERATION

FIGURE 1: SIMPLIFIED DIAGRAM OF MOUNTAIN VIEW PLANT

recycled to the suction of the compressor. From the adsorber, treated gas is compressed to 400 psig for injection into PGandE's line 101 which serves the San Francisco Peninsula. Control is accomplished with a densitometer which monitors treated gas specific gravity and adjusts cycle time accordingly.

Construction of the treatment plant was completed in May, 1978. Table I shows a breakdown of the plant's costs. EPA's contribution amounts to $270,000. Corresponding to yearly revenue requirements of $288,250 as is usually done in the utility business, the cost of the gas is $2.95 per MMBtu. Thus, treated landfill gas is competitive with imported Liquefied Natural Gas and Synthetic Natural Gas from coal.

Start-Up and Operation

Following completion of the facilities in May, 1978, the plant was started-up in early June. Since then, it has operated sporadically for about 230 hours. This spotty performance can be attributed to the following:

- Failure of a desiccant support screen in one of the adsorbers resulted in the introduction of alumina powder in the vacuum cylinder. The cylinder wall and rod were scored. New rings, packing and valves were installed on the vacuum stage. The cylinder was honed. Also, a filter was installed upstream from the vacuum stage.
- Moisture adsorption by the molecular sieves caused the plant to fail to operate at design capacity of 1 MMSCFD. The plant design requires the adsorber packing to separate carbon dioxide from the raw gas during a design cycle of twenty minutes. Carbon dioxide breakthrough was registered after six to eight minutes. It is not known when and how moisture adsorption took place. It might have happened while the sieves were in storage for about one year at PGandE's Decoto yard or during the early phases of start-up. In any event, the presence of moisture and other volatiles was revealed by a drying test of sieve samples from all three adsorbers which averaged 11.7% volatiles by weight. Late in November, the adsorbers were regenerated with heat generated in a temporary gas-fired heater rigged up for this purpose. On the average, each tower was heated with hot methane to about 600°F for about ten hours. Approximately 55 gallons of condensate per adsorber were produced during the regeneration cycle. Samples of the condensate taken at various stages of the cycle are being analyzed by West Coast Technical Service, Inc. using combined gas chromatography-mass spectroscopy.
- Inadequacy of the vacuum system to pull the design vacuum of 26" Hg. The best that can be achieved with the system at present is about 20" Hg.

Four corrosometers installed on the knockout pots and the air-cooled condenser have registered corrosion rates ranging from 15 to 30 mills per year. PGandE's engineers fully expect corrosion to be eliminated as a practical problem with the injection of an inhibitor in the raw gas.

Following heat regeneration of the adsorbers, the plant was operated at design capacity of 1 MMSCFD of raw gas for 30 hours. Treated gas composition averaged 98% methane.

TABLE I

LANDFILL GAS TREATMENT COSTS[1]

	Equipment Costs, $	Installed Cost, $
Adsorbers	245,000	410,000
Compression[2]	200,000	390,000
Analytical Equipment		10,000
Wells and Collection System		30,000
TOTAL INSTALLED COST		840,000[6]
YEARLY COSTS		$/YR
Maintenance[3]		27,700
Manpower		30,000
Fixed Charges[4]		208,300
Feedstock Costs,[5] @ $0.16/MMBtu and 139,000 MMBtu/yr		22,250
TOTAL REVENUE REQUIREMENTS		288,250
Energy Output, MMBtu/yr[7]		97,650
Energy Cost, $/MMBtu		2.95

1) Basis: 1 MMSCFD of raw landfill gas with a heating value of 450 Btu/scf.

2) Based on injection pressure of 400 psig.

3) Maintenance = 2% of adsorbers' installed cost plus 5% of compressor's installed cost.

4) Fixed charges = 24.8% of total installed cost on the basis of a 10-year life. They include: depreciation, interest, profit, federal and state taxes, insurance, etc.

5) Reflects initial payment of $0.072/MSCF of raw gas to the City of Mountain View.

6) Of this total, EPA's contribution amounts to $270,000.

7) Based on thermal efficiency of 70% and on-stream factor of 0.85

On the basis of data collected since June, 1978, PGandE is confident that the plant will operate as designed.

Future Plans

As agreed upon in the contract signed by PGandE and the City of Mountain View on November 26, 1975, PGandE has informed the City of Mountain View of its plan to initiate the demonstration phase of the project on January 2, 1979. The demonstration phase is designed to establish the technical and economic viability of the landfill gas recovery concept. It will last twelve months, unless both parties agree to extend it. Following completion of the demonstration phase, the plant, if successful, will be expanded to treat the full production of the landfill, or about 5 MMSCFD.

Specifically, the demonstration phase will involve the following:

- An evaluation of corrosion in the process equipment and of ways to minimize it.
- Comprehensive chemical and biochemical analyses of all gas and condensate streams.
- An analysis of the impact of air intrusion on the processing and utilization of gas recovered at Mountain View.
- Production on a continuous basis of treated gas that meets design specifications (less than 3% CO_2, 7 lbs. of H_2O per MMSCF of treated gas, less than 4 ppm H_2S, etc)
- Confirmation of landfill gas recovery economics.

PGandE, in collaboration with Dynatech R&D of Cambridge, Massachusetts, has submitted a proposal to the Department of Energy (DOE) that encompasses the program for the demonstration phase. Negotiations with DOE are expected to take place soon.

Recognition and Contributions

I am indebted to the following:

1. Messrs. R. Holden and R. Headrick of PGandE's Gas System Design Department.
2. Mr. M. R. Lee of Gas Utilization Department.
3. Messrs. E. C. Remedios, R. F. Goldstein, and R. E. Hodgen of Gas Resources Department.
4. Messrs. A. Garrissere and R. Savullo of PGandE's San Jose Division.
5. Messrs. J. R. Bean and M. D. Orton of Gas Distribution Department.
6. Mr. Ray Boyle of General Construction - Gas.
7. Mr. W. Culver of the Department of Engineering Research.

References

1. "Final Environmental Impact Report for NRG Nufuel Co's landfill gas processing system, City of Rolling Hills Estates" by VTN Consolidated, Inc., January 1975.
2. "Methane Recovery Demonstration Project - Engine Generator Set Operation Report" by the L.A. Department of Water and Power, October 1975.
3. "Methane from Landfills - Survey of Existing Bay Area Sites" by J. W. Van Zee for PGandE, August 1974.
4. "Treatment and Utilization of Landfill Gas - Mountain View Feasibility Study" (SW-583) prepared by PGandE for EPA, 1977.

5. "Recovery of Landfill Gas at Mountain View/Engineering Site" Study prepared for EPA by the City of Mountain View, EPA/530/SW-587d, May 1977.

ANAEROBIC DIGESTION OF AGRICULTURAL RESIDUES - A TECHNOLOGY ASSESSMENT*

Tom P. Abeles & David Elsworth
i e associates, inc.
3704 11th Ave. So.
Minneapolis, MN 55407

&

John P. Genereaux
Genereaux Social Science Consultants
370 Summit Ave.
St. Paul, MN 55102

ABSTRACT

Field evaluation of a full scale farm digester was carried out for over a year to ascertain the engineering design problems needed to bring farm scale systems to commercialization. This work was enhanced by laboratory analysis of a variety of potential feedstocks including municipal solid waste. On-site inspection of a number of pilot plants coupled with a literature investigation, economic analysis and farmer survey indicates that these systems are viable on gas-only economics for farm systems as small as 100 dairy cows or the equivalent and perhaps as small as 32 dairy units provided careful planning is carried out and full use is made of the gas. Financial incentives and government support would not only enhance the viability but would probably accelerate adoption of the technology.

Several areas of research and development are in need of attention to assure the success of these systems and to provide opportunities for better yields and a wider choice of feedstocks. Simple, low-cost pretreatment processes are not yet available to allow a variety of organic residues from municiple solid waste to crop residues to be used effectively and to allow a greater fraction of the organic material to be converted to energy. More effective tank designs coupled with improved anaerobic populations are needed. Careful attention must be paid, also, to uses of effluent for refeed, fertilizer or innovative alternatives such as greenhouses, algal culture and aquaculture.

Very little work has been done on potential social and environmental impacts of either small scale or large commercial systems for use of organic residues. Potential changes in farming operations, energy use patterns and animal feed options are in need of examination. Conversion of methane from organics to methanol may prove viable in the near term. This may favorably impact the methanol/ethanol/fuels issue now prominent.

INTRODUCTION

The anaerobic process for conversion of organic materials to methane and carbon dioxide is found in nature at ambient temperatures at the bottom of lakes or at 37°C in the digestive systems of cattle. The process is exothermic as evidenced by rise in temperature in landfills during methane production; but gas production is enhanced by the addition of heat which reduces the amount of time for conversion of the material to gas.

*Work supported in part under USEPA Contract #R-804-457-010 and the Office of Technology Assessment (U.S. Congress) Contract #OTA-C-78-357.

This process has been used for years in the western hemisphere as a means for stabilization of sewage prior to disposal. In the Far East and India, the need for energy and fertilizer has generated the development of low cost, simple digesters for production of gas for use on farms and in rural homes. With the growing concern over dwindling energy resources, research, owner-built digesters and pilot plants have been established in the U.S. and abroad to produce energy using farm residues and organic wastes. The key to the technology has been in the development of systems which is amenable to western farm operations. This means simple systems without the eastern labor intensiveness and mechanical systems with the reliability but not the inherent cost of sewage treatment plants. Economics has to be shown using the present level of technology since there is no clear evidence that any research will achieve an order of magnitude breakthrough in gas production or economics in the near future.

In the case of cattle and hog wastes, part of the economics is achieved through the development of flexible membrane tanks which use a no-mix plug-flow design and which can be easily installed by an owner-operator. This work shows that a key to economic success is the proper matching of gas production with load needs or total use of gas for power and heating where applicable. Finally, some system cost analyses are based on use of the effluent in innovative ways such as algal culture, aquaculture or animal refeed as well as fertilizer.

When electricity is produced, significant quantities of waste heat are available. Unless this is used (cogeneration), economics may become negative. The addition of a greenhouse or other sink serves as an alternative. The greenhouse may produce a significant income which could exceed that of the primary farm production. This indicates that careful attention must be paid to socio/economic changes as well as bio/physical environmental issues in the introduction of this technology.

PROCESS DESIGN

Microbiology - In general, one may consider the biological process as a three phase operation; pretreatment or hydrolysis, acidification and methanation. For farm scale systems the pretreatment or hydrolysis phase be it acid. basic or enzymatic hydrolysis, is currently too costly and premature in its development. This limits the feedstock to those materials which are readily usable by the anaerobic process. In this research the feedstocks were animal wastes with some laboratory work done on municiple solid waste and algae. Other materials which were considered included waterborn biomass such as kelp, algae and water hyacinth. Since the primary area for application was the Upper Midwest, only algae was given serious consideration.

The interest in algae was twofold. First, it has been suggested that one possible microbiological rate limiting step was the availability of hydrogen to the menthanogenic bacteria. Secondly, algae could serve as a means of concentrating the effluent in the form of biomass and could serve as either digester feedstock or high protein feed. Research focused on Dcenedesmus and obliques which can evolve hydrogen during growth. The concept was to feed the evolved hydrogen to the digester and enhance the methanogenic process. The postulated nominal conversion mechanisms might be reduced to:

$$\text{organic matter} \xrightarrow{\text{bacteria}} CH_4 + CO_2$$

$$CO_2 + 4H_2 \xrightarrow{\text{bacteria}} CH_4 + H_2O$$

If one looks at the heats of combustion on a molar basis, the hydrogen contains about 17% more potential energy than the methane which can be produced by the above conversion pathway. What is unknown at this point is whether the postulated conversion is actually on a 4:1 basis or whether the route is more complex. Time and funds prevented the development of this concept beyond the preliminary laboratory phase. It is possible to develop a solar collector which uses hydrogen producing algae as the working fluid. Such a unit has potentials for enhancing the fermentation process by biomass, hydrogen and thermal inputs.

Another area of potential interest is the possibility that the microbial populations adapt to substrates. This implies that not only can the process be carried out in different biochemical regimes, but that there is the possibility of obtaining a population which has a higher conversion yield or efficiency. Work on swine wastes (2) has shown that good gas yields can be obtained at alkalire pH which, hithertofore had been projected as toxic to the microbial process. Recently, work done for the Gas Research Institute (3) on kelp digestion has shown that selected strains can be obtained which produce the same volume of gas per unit biomass and within the same time at ambient as the optimally operated mesophillic systems. They also indicate that currently, kelp does not yield readily to thermophillic digestion.

Because of the variance in data from different publications, research was initiated using thirteen identical digester units. The quantity was the minimum number which could have statistical significance. Holstein dairy waste was used in a solution of approximately 10% solids for 7 weeks to assure stabilization and then the mixture was shifted to 63% manure:37% municipal solid waste for 5 weeks. All data was then analyzed using a standard statistical package available through the University of Wisconsin-Madison's Univac 1110. Tables 1 and 2 indicate the results for the two feedstocks where ANOVA indicates "analysis of variance". The ANOVA shows that the effect of time on biogas production is statistically significant (p 0.00.), meaning that the digesters behave differently from day to day. However, because the interaction of time x feedstock is also statistically significant (p 0.001), the averages for each 14 day period should not be combined. In other words, biogas production in the feedstock 2 phase was lower than in the comparable phase for feedstock 1. Table 1 shows the grand mean for feedstock 1 to be 583 mls/day; for feedstock w it is 568 mls/day, a difference of 15 mls/day. While the feedstock , mixed with the municipal solid waste did produce less gas than the animal wastes alone are indications that gas production increased. The experiments should be repeated with larger concentrations of municipal solid waste and attempts should be made to select a favorable microbial population. The work for the Gas Research Institute focused on developing specific populations from decaying kelp on the ocean floor. For municipal solid waste, one may look toward species indigenous to landfills. Another source might be detritous in tropical areas which may have a predilection toward lignocellulosic materials. Methane production has been observed in the wood of living trees which are suffering from decay. This offers another alternative source of microbial populations.

Systems Engineering - Based on the microbiology, a number of systems designs have been proposed from simple one tank, unmixed units to multiple tanks which separate the acid and methanogenic phases and are completely mixed. For farm scale systems, the current state of the art suggest that a single tank which is maintained in the mesophillic region (37°C) is the best design. Work at Cornell (3) and full scale commercial systems (4) indicate that simple plug flow units operating with diluted or undiluted wastes, maintained at mesophillic temperatures without mixing,appear to be the most appropriate for cattle waste. Smith (5) has indicated that the energy for mixing does not seem to warrant the extra cost in terms of enhanced digestion,either in shortened retention times or ease of operation. This is supported by the Cornell studies.

In this study, four systems were investigated, an intermittent mix pilot plant

Table 1: A Comparison of Means, by Feedstock, Over Time

	TIME*														
Feedstock	1	2	3	4	5	6	7	8	9	10	11	12	13	14	$\bar{x}$
1	535	643	549	627	641	518	612	507	593	639	524	581	623	569	583
2	494	572	589	509	582	615	489	533	512	627	534	625	640	638	568
$\bar{x}$	515	608	569	568	612	567	550	520	553	633	528	603	632	603	576

*Time 1 in this table corresponds to day 34 for feedstock 1, day 69 for feedstock 2; time 14 corresponds to day 47 and 82, respectively.

Table 2: Average Biogas Composition For 13 Digesters

Day No.	CH_4/CO_2	$\%CH_4$	$\%CO_2$	$\%N_2$	$\%O_2$
2	2.62	39.5	15.1	-	-
9	1.45	54.9	37.8	6.44	1.04
16	1.41	55.4	39.3	4.32	1.04
23	1.38	54.5	39.5	5.15	0.94
30	1.21	52.4	43.4	3.63	0.72
37	1.27	53.8	42.5	3.07	0.67
44	1.31	53.5	40.9	4.69	0.92
51	1.13	50.5	44.5	4.18	0.83
58	1.15	50.5	44.1	4.56	0.90
65	1.26	52.7	41.7	4.65	0.95
72	1.34	54.3	40.4	4.31	0.94
79	1.28	53.7	41.9	3.46	0.91
$\bar{x}$, 9-79	1.29	53.3	41.5	4.39	0.90
$\bar{x}$, 9-44*	1.34	54.1	40.6	4.55	0.89
$\bar{x}$, 51-79#	1.23	52.3	42.5	4.23	0.90

*Represents the average for the period covering steady-state operation with feedstock 1.

#Represents the average for the period of operation covering feedstock 2.

Table 3: Comparison of Biogas Production Efficiency

	Feedstock 1	Feedstock 2
measured biogas production		
mls of biogas/ml influent	11.7*	11.4*
%TS in influent	7.6#	4.93
%VS of TS in influent	83.0#	84.7
%VS destruction	24.0#	24.6
ft^3 biogas/lb TS_A	3.79	3.69
(m^3/Kg TS_A)	0.236	0.229
ft^3 biogas/lb VS_A	4.56	4.35
(m^3/Kg VS_A)	0.285	0.270
ft^3 biogas/lb VS_D	18.2	17.7
(m^3/Kg VS_D)	1.14	1.10

*Based on the average biogas production results from the ANOVA.

#No samples of influent or effluent were taken in the feedstock 1 phase; these values represent averages from a previous study in which the same type of influent was used; they also are consistent with results from other, similar studies.

at the University of Wisconsin-Green Bay, a 100 horse digester constructed from brewery tanks in Neenah, Wisconsin, a "bag" digester in Custer, Michigan and a tank digester in Rice Lake, Wisconsin. The latter two systems were designed and constructed under the supervision of Agricultural Energy Corporation, Luddington, Michigan. Both are plug flow, mesophillic, unmixed systems.

During the entire study, all systems ran under design loading and had no problems maintaining thermal and biochemical balance within the digestion unit. Rather, all suffered severely from mechanical problems and the lack of adequate engineering. The basic problems came from waste handling during the feeding cycle of the operation. The horse digester, which was largely owner designed, did not take into account the extensive amount of bedding needed for show horses. Thus collection and mixing of manure became such a severe problem that the unit was abandoned because operational costs exceeded net benefits from the gas production.

The pilot plant ran with minimal problems. The main problem was the reliability of the pump chosen to feed the tank. This item appeared to be the key problem with all the systems including others (outside of this investigation) with which the authors are familiar. For example, the Custer digester received manure from an open feedlot which picked up straw and animal hairs. Attempts at maceration led to fouling of the incinerator with animal hairs, while pumping was hindered by long straw and occasional winter freezeovers of the feedlot.

Freezing hampered the Rice Lake unit which had a temporary feed system for testing turkey wastes. Insufficient hydraulic pressure to drive the pumps also became an issue at Rice Lake.

The turkey wastes pointed out handling problems which will also be prevalent in broiler operations and feedlots which are only cleaned periodically. Aged manure does not mix, sell or pump easily and materials from unpaved floors tend to accumulate detritus such as rocks and other extraneous materials. Additionally, the aged materials loose volatile nutrients such as nitrogen which lower gas production. Also, rice hulls were used as bedding for the turkeys. This material does not digest readily as confirmed by observation and analysis, which showed over 60% inorganics and fibrous material.

Figures 1 and 2 are schematics of the Luddington and Rice Lake systems. The Luddington unit is a fabric reinforced "plastic" bag while the Rice Lake unit is made of galvanized culvert. The bag unit is low in cost, easy to install and relatively trouble free. It can take cold climates and is insulated with styrofoam sheets which float on the surface of the material. The Rice Lake unit is more costly to manufacture and has only been in operation for two years. It is too early to tell how the metal will behave over time. Zinc is known to be toxic to anaerobic species, but no evidence of inhibition has been found. Also, corrosion is anticipated to be minimal in the absence of air as has been experienced in a number of units with internal metal parts which were kept oxygen free. It is difficult, though, to exclude all air when pumping in new effluent, so problems may arise in the future.

Both the Custer and Rice Lake units used the gas produced to drive an engine/generator set. Though hydrogen sulfide in the gas and influent did discolor the copper piping in the mechanical sheds, routine investigation of the internal parts of the engine after biogas operation indicated that the scrubbers acted effectively to protect the units. Waste heat from the generator units provided the heat for the digester with excess heat vented. This is a crucial factor in the economics but not in systems operation.

SOCIO/ECONOMICS

Social Issues - Outside of technological blocks, it became important to identify those issues which were significant in encouraging or blocking widespread adoption. A survey of farmers was conducted in 1974 in Brown County, Wisconsin. A similar study was conducted in 1978 in Barron County, Wisconsin, and currently (December 1979), a pretest survey of farm energy needs, uses and attitudes on waste managment was conducted in Ottertail County, Minnesota. The object of the first two surveys was to test farmer attitudes toward adoption of digesters, while the final

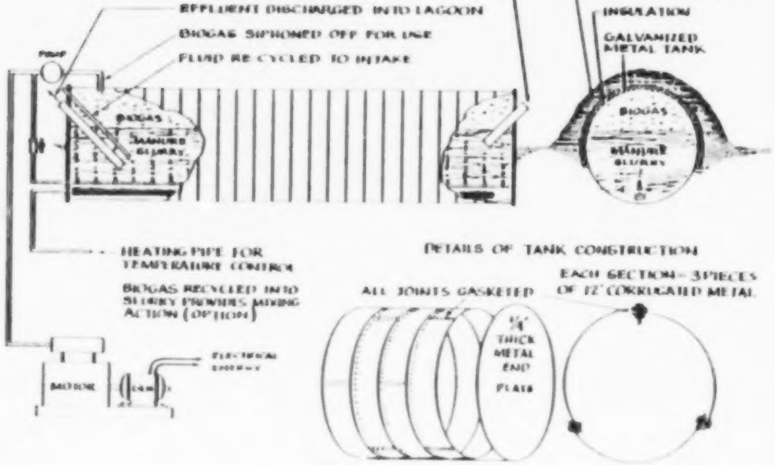

SLURRY PUMPED INTO TANK
EFFLUENT DISCHARGED INTO LAGOON
BIOGAS SIPHONED OFF FOR USE
FLUID RE-CYCLED TO INTAKE
PUMP
BIOGAS
MANURE SLURRY
EARTH COVERING
INSULATION
GALVANIZED METAL TANK
BIOGAS
MANURE SLURRY
HEATING PIPE FOR TEMPERATURE CONTROL
BIOGAS RECYCLED INTO SLURRY PROVIDES MIXING ACTION (OPTION)
MOTOR
ELECTRICAL ENERGY
DETAILS OF TANK CONSTRUCTION
ALL JOINTS GASKETED
EACH SECTION - 3 PIECES OF 12' CORRUGATED METAL
¼" THICK METAL END PLATE

Figure 1: Rice Lake Fermentation Tank

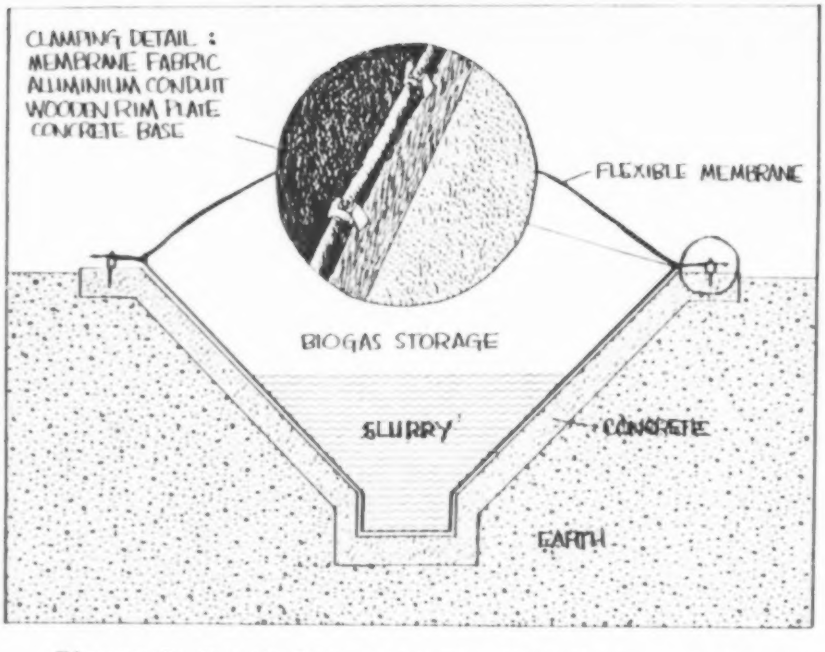

CLAMPING DETAIL :
MEMBRANE FABRIC
ALUMINIUM CONDUIT
WOODEN RIM PLATE
CONCRETE BASE
FLEXIBLE MEMBRANE
BIOGAS STORAGE
SLURRY
CONCRETE
EARTH

Figure 2: Earth Supported Flexible Membrane Digester
Operation similar to Figure 1

full survey will be carried out in the spring of 1979 to ascertain potential problems in carrying out energy conservation and alternative energy system development in midwest animal operations. Appendix A summarizes the factors which appeared crucial to the adoption of agricultural innovation.

Several significant factors appeared outside of the basic attitudinal information. First, there is no extant infrastructure for constructing, servicing and supporting these systems within the standard agribusiness context. Next, there exist few, if any, codes which outline safety practices and operational procedures that would allow such parties as banks and insurance companies to deal with these systems. Finally, it was uncertain at the time of the research where governmental support would come from since few farms qualified under any of the EPA guidelines for pollution abatement. Since then, DOE and USDA have started exploring funding mechanisms,and several states have included provisions within their solar legislative package.

Economics - Technical feasibility was never of primary concern; rather, technical feasibility within the context of economic viability has been the key issue.

The analysis of methane production for farms show that it can be a complex and capital intensive investment if traditional "turnkey" engineering approaches are taken. On the other hand, the systems in the Far East have been proven to be simple and low cost. Research in this country by Jewell and others (3) indicates the possibility of simple, owner-built units which can significantly change the capitalization economics. A simple digester suitable for a 60 cow operation or the equivalent could cost under $10,000, including all pumps and controls necessary for a modern U.S. farm operation.

When examining these non-traditionally engineered systems, it is found that the more favorable economics is predicated on some changes either in farm operation or life-style. This not only allows for better energy utilization but may imply indirect energy and economic benefits that may outweigh the direct gain from either the gas value or effluent enhancement. For example, efficient digester operations are essential. This implies complete use of all the outputs such as heat, electricity and effluent. An engine/generator produces extensive amounts of waste heat which can be costly unless a "sink" such as a greenhouse is found. The ramifications of a greenhouse for farm income could be substantial. A quick estimate shows that the waste heat from a 100 cow digester-engine/generator can supply sufficient heat for a greenhouse of the size which could have an income larger than the dairy producing the waste.

Since economics depends on efficient gas utilization, farm operations may have to be changed to accommodate the new system. For example, few farms are currently on natural gas in the midwest. Many of these utilize electricity for such functions as cooking, hot water heating, some space heating and similar activities. The cost is likely to affect the small systems since any changes are reflected in the system capital cost; yet, it is those systems which must use the gas most effectively to be economically viable.

The added cost of a generator on a small system may be even more costly, even with the ability to credit retail price of electricity in the economic evaluation. This may be reflected at several levels. First, a generator which is sized to burn all the biogas will probably not have its output used 100% of the time. Next, a generator which operates at reduced loads (like a base loaded power plant) may place the farm in the position of being billed by the utility for peak power utilization. Finally, if the gas is burned 100% for power, waste heat will probably be dumped because it cannot be stored; whereas, a baseloaded generator with gas left over will have competition between unburned gas and waste heat for thermal displacement.

Thus, on small farms, with limited flexibility, extreme care in design is necessary. Also, the small farm favors direct gas use rather than conversion to power. For larger systems, more flexibility exists for integration and optimum economics.

Tables 1 and 2 in Appendix B are summaries of the economic feasibilities of selected systems across the United States. Average sized farming operations within the appropriate regions were chosen using the best available data. For all systems the following financial assumptions have been made:

1. An investment tax credit of 7% applies to the investment in the first year.

2. An accelerated depreciation of 30% is taken in the first year. Depreciation of 10% follows for the next seven years. Depreciation is set against a taxable income of $15,000,00, with four exemptions for the state of Minnesota. (Tax break of 35%.)

3. All tax credits are amortized over the twenty-year life period of the equipment.

4. Since the equipment is energy productive, it is assumed that no property taxes will be levied against it.

5. Discount rates of 9% over a twenty-year system life are used.

6. Insurance costs are assumed to be .5% of investment.

The net tax relief over the twenty-year life of the equipment is $42.00 per $1,000.00 of investment per year; insurance is $5.00 per year.

For large systems (over 200,000 gal.) which sell refeed, one technician, at $15,000.00/year, is assured to be required to operate the plant and accomplish the more intricate day-to-day management at this level. Large systems without refeed are assumed to require one-third man-year for operation.

It should be emphasized that this is for mature systems and may have little application to the prototypes which have been developed for near future use.

As can be seen from the tables, individual systems have good feasibility under high refeed value on fertilizer enrichment assumptions. Relatively few are profitable, however, at direct energy supply levels alone. Exceptions are limited to large poultry operations, which have high energy needs and thus provide their own best market.

Interestingly, when waste heat is added to direct heat (Table 2, Column 13), most systems appear feasible.

Climatic factors appear important to feasibility of direct energy use only in turkey operations in Minnesota vs. California and North Carolina. The same was true of broilers, at least in a comparison of Arkansas to Minnesota in the smaller broiler operation shown.

Hog, dairy, and laying hen operations, do not show significant climatic effects on overall feasibility.

In fully examining the economic data, one sees that feasibility is dependent on utilization of the output from the system whether it is effluent or gas and concomitant by-products. The best return from the gas would be through cogeneration provided that the waste heat from the generator could be recaptured and used efficiently. A large heat demand is found in northern areas for such operations as broilers and other fowl and swine rearing activities. This can be seen from a comparison of the Arkansas and Minnesota data. The parallels with solar feasibility in this regard are quite good.

What has not been discussed previously is the impact that new or other near term technologies might have on the economic feasibility. Fuel cells are one such technology which could enhance overall efficiency and economics. These units have a higher power conversion efficiency which does not require the large recovery and use of waste heat. Also, unlike generators, the fuel cells maintain this conversion efficiency under partial load, adding further to economic efficiency.

Another point to note is that many of the systems show a net return or positive contribution prior to any tax or depreciation credits. Many systems in the tables also show only minor potential profits or losses. These latter systems could be enhanced by slight changes in fuel prices or tax incentives for renewable energy systems. Thus, for these engineered (or constructed-for-profit) systems economic incentives would make digesters an economically attrative option. If systems were owner-built, the economics look even more favorable.

An important point to re-emphasize,

though, is the fact that many systems do not show profitability on energy alone. The exeptions are turkey and large boiler operations which are extremely energy intensive in their operation. Even these show a potential, energy only, return without tax credits. The real return appears to be in the "enhanced" value of the effluent for use as refeed or fertilizer.

In the U.S., a large portion of the digester work has been done on dairy and beef operations, and the data in the tables shows some interesting facts for these commercially installed systems. For systems as small as 32 dairy cows in cold regions, the loss is only about $300/year with the current tax structure, while "energy only economics" show a significantly larger loss for a California herd size of over 300 head. First, this implies that a good end use of the gas is needed. Next, it indicates that any factors which cut the net costs to the small dairy farmer or small farm operator such as owner-built systems, tax incentives or fuel credits could make these units a profitable operation.

CONCLUSIONS

The process of anaerobic digestion is both technologically and economically feasible in the U.S. currently. The basic problems are primarily socio/economic in that an extant infrastructure is not available to design, construct, or maintain and service these systems. Some minor engineering problems primarily in the area of materials handling need to be solved, but these are largely a result of a lack of extensive experience in the U.S. with intermediate scale systems.

The systems will prove even more viable as energy costs rise and as second generation systems are developed. Some of the potential needs for these new systems are: selected microbial populations to enhance organic pretreatment and digestion, more efficient conversion systems for using the biogas, and a supporting infrastructure including participation by utilities in optimizing biogas use. Also, work needs to be done on the use of the effluent (1) by animals in such areas as health effects and feed values, (2) for aquaculture, (3) for algal culture (for use of both the effluent and waste heat) and (4) for fertilizer management.

These units could also be very important in rural cooperative systems and integrated farm and community energy systems which provide energy and waste management for rural communities or groups of farms.

REFERENCES

1. Lapp, H. M., et al, Start Up of Pilot Scale Swine Manure Digesters for Methane Production, in Managing Livestock Wastes, Proc. 3rd ISLW Conf., Urbana-Champaign, Illinois, April, 21-24, 1975.

2. Chynoweth, D. P., et al, Biomethanation of Giant Brown Kelp, Macrocystis Pyrifera, Institute of Gas Technology Symposiu, Clean Fuels from Biomass, Washington, D.C., 1978.

3. Anaerobic Fermentation of Agricultural Residues, U.S. Department of Energy Rept. #HCP Jewell, W. J., et al, Bioconversion of Agricultural Wastes for Pollution Control and Energy Conservation, Cornell University, Ithaca, NY, 1976 (TID-27164).

4. Abeles, T. P., et al, Energy and Economic Assessment of Anaerobic Digesters for Rural Waste Management, OASIS 2000, Rice Lake, Wisconsin, 1978.

5. Smith, K. D., et al, Design and First Year Operation of a 50,000 Gallon Anaerobic Digester at the State Honor Farm Dairy, Monroe, Washington, Ecotope Group, Seattle, Washington, 1978.

Appendix A: Factors Underlying the Adoption of Agricultural Innovations

(Factor)	(Relative Importance/Comment)
Cost	
1. Initial cost	Not an important deterrent
2. Continuing (operating) costs	Minor significance
Returns	
3. Rate of cost recovery	Minor significance
4. Monetary payoff	Significant
Profitability	
5. Extent of economic advantage over alternatives	Significant
6. Replacement status (condition) of existing equipment	Significant
"Efficiency"	
7. Saving of time	Minor significance
8. Saving of discomfort	Minor significance
Risk and Uncertainty	
9. Regularity of reward (Shows results every time)	Significant
10. Divisability for trial (How easy to try; first, on a small scale)	Significant
Congruence	
11. Association with main enterprise (dairying)	Significant
12. Advantage (overall significance of the practice for the entire farm program	Significant
13. Pervaiveness (of consequences of adoption; leads to other changes or practices)	Not an important deterrent
Communicability	
14. Complexity (of understnading and use)	Minor significance
15. Clarity of results (How clearly do results show?)	Minor significance
Farm Characteristics	
16. Farm size (total acreage, dairy herd size)	Significant
17. Location of farmstead (proximity to others; coop unit possibilities)	Significant

Farm Financial Position

18. Capital (Curvilinear effect; Proxies-estimated value of land, buildings, equipment, and livestock)	Significant
19. Current income (Proxies-gross farm sales, milk receipts)	Significant

Farmer Characteristics

20. Age	Significant
21. Education	Significant
22. Tenure (owner/renter)	Significant
23. Years farmed	Significant predicator of adopting environmental measures
24. Attitudes and values (proxies-affiliation with farm organizations, activity with social groups, contact with "science" via reading magazines and extension bulletins)	Significant

Regulatory and Legal

25. Pollution control (manure handling rules and policy)	Significant
26. Safety requirements	Precondition
27. Zoning and land use regulations	Precondition

Institutional and Infrastructure

28. Availability of technical support (engineering firms, university extension)	Condition for widespread adoption
29. Convenience of repair and maintenance services	Condition for widespread adoption
30. Supportive (and familiarity with the innovation) farm finance and insurance sector	Condition for widespread adoption
31. Information sources (mass media-radio, TV, newspapers and magazines; friends and neighbors - mostly other farmers; agricultural agencies - univ. ex., SCS, farm credit agencies, and the like; vendors and potential suppliers)	Significant for diffusion

The factors listed above were adopted, with modifications and expansion from:

Cancian, Frank, "Stratification and Risk-Taking: A theory Tested on Agricultural Innovation", *American Sociological Review*, 1976.

Fliegel, Frederick C. and Joseph Kivlin, "Farm Practice Attributes and Adoption Rates", *Social Forces*, 1962.

________________, Attributes of Innovations as Factors of Diffusion", *American Journal of Sociology*, 1966.

Kronus, Carol L. and J. C. van Es., "The Practice of Environmental Quality Behanior", Journal of Environmental Education, 1976.

Mansfield, Edwin, The Economics of Technological Change, W. W. Norton, 1968.

Pampel, Fred, Jr., and J. C. van Es, "Environmental Quality and Issues of Adoption Research", Rural Sociology, 1977.

Table 1
System Feasibility of Anaerobic Digestion on Single Livestock and Poultry Farms in Leading Producer States, 1978.

Livestock State Avg. No.	Energy Benefits[a]/Year ($1,000)			Benefits from By-Products ($1,000/Yr.)			
				Fertilizer Enrichment		Refeed	
	KWh (retail) @ 4¢/KWh	BTu @ $5.4/BTu 10^6	2.5¢/KWh	@ $10/dry ton	Cost of App. extra[k]	@ $23/dry ton	@ $90/dry ton
Turkeys (sold)							
Minnesota 124,000	9.9	38.5	19.1	12.5	6.1	28.2	112.8
California 98,000	5.9	20.5	13.7	9.8	4.8	22.3	89.2
No. Carolina 89,000	6.4	9.0	11.7	8.9	4.4	22.2	91.0
Broilers (sold)							
Minnesota 52,000[m]	0.0	2.7	0.0	.5	.2	1.2	4.8
198,000[b]	2.8	8.2	1.4	2.0	.8	4.5	18.0
California 56,000[m]	0.0	2.6	0.0	.6	.2	1.3	5.2
1,377,000	9.2	36.1	14.6	13.7	5.8	31.0	124.0
Arkansas 63,200[m]	0.0	1.8	0.0	.6	.3	1.4	5.6
186,000	2.9	6.2	1.6	1.9	.8	4.2	16.7
Swine (sold)							
Iowa 1,600	0.0	2.4	0.0	1.1	.3	2.4	9.4
Missouri 1,600	0.0	2.4	0.0	1.1	.3	2.4	9.4
No. Carolina 1,600	0.0	2.4	0.0	1.1	.3	2.4	9.4

Table 1 - Continued

Livestock State Avg. No.	Energy Benefits[a]/Year ($1,000)			Benefits from By-Products ($1,000/Yr.)			
				Fertilizer Enrichment		Refeed	
	KWh (retail) @ 4¢/KWh	BTu @ $5.4/BTu 10^6	2.5¢/KWh	@ $10/dry ton	Cost of App. extra[k]	@ $23/dry ton	@ $90/dry ton
Dairy Cows (Inventory)							
Wisconsin							
32	0.0	1.4	0.0	.6	0.0	1.4	5.7
New York							
64	0.0	1.4	0.0	1.2	0.0	2.8	11.3
California							
337	5.0	2.4	.8	6.4	0.0	14.9	59.6
Laying Hens (Inventory)							
Minnesota							
12,922	0.0	1.3	0.0	1.6	.25	3.6	14.3
41,405	4.0	1.7	2.2	5.0	.81	11.4	45.7
Georgia							
13,500	0.0	.8	0.0	1.6	.26	3.7	14.8
40,800	4.1	1.1	2.0	5.0	.80	11.3	48.1
California							
14,300	0.0	1.1	0.0	1.7	.28	3.9	15.8
105,200	19.0	3.9	0.0	12.8	2.1	29.1	116.8

Notes:
b. Assumes electric need of .26 KWh/bd + 2 houses @ 18,700 KWh/yr. retail; rest wholesale @ 2.5¢/KWh.
c. Assumes 9-month storage lagoon for feedstock.
d. Assumes 2-month capacity lined, covered pit for feedstock + cost of extra pump.
e. Assumes 3-month storage lagoon for feedstock.
f. Assumes 1-month storage lagoon for feedstock + cost of extra pump.
g. Assumes 50% of waste heat available.
h. All waste heat is assigned to greenhouse or neighborhood heat distribution sources.

Table 1 - Continued

Special Costs/Yr. ($1,000)		Use for Waste Btu ($1,000 @ $4/Btu 10^6)		Net System Costs & Benefits ($1,000/yr.)						Special Savings ($1,000/yr)
Sealed Manure Pit	Residue Lagoon	Greenhouse Heat	Manure Drying For Refeed	Energy replacement & Fertilizer Enrichment only (Energy only)	Energy & Refeed Value		Energy, Fertilizer & Foil Waste Heat Use 70% (energy & heat only)	Energy, Refeed & 40% Use of Waste Heat^1		Manure Disposal
					$23	$90		$23	$90	
9.2^c	1.1^d	9.6^g	9.6^g	43.9 (30)	50	134	50.9 (38)	51	135	6.1^i
7.8^c	$.3^e$	11.2^g	11.2^g	18.7 (9)	23	90	26.7 (17)	47	94	4.8^i
7.4^c	$.3^e$	13.8^g	13.8^g	40.0 (.1)	11	80	15.4 (7)	17	86	4.4^i
1.0^f	$.3^d$	0.0	0.0	-1 (-1.5)	1	3.7	---	--	--	$.2^i$
2.0^c	$.3^d$	0.0	0.0	-1.4 (-3.4)	-9.4	4.1	---	--	--	$.8^i$
1.1^c	0.0^e	$.7^h$	0.0	-.8 (-1.4)	.3	3.9	-.3 (-.9)	.6	4.2	$.2^i$
5.7^f	$.3^e$	9.1^g	9.1^g	41.7 (28)	0	93	48.1 (35.6)	3.6	96.6	5.8^i
1.2^c	0.0^e	1.1^h	0.0	-3.8 (-4.4)	-2.4	1.8	-3 (-3.6)	-2	2.2	$.3^i$
2.0	.3	1.4^g	1.4^g	.2 (-1.7)	-5.5	7.0	1.2 (-.7)	-4.9	7.6	$.8^i$
	$.1^d$	0.0	0.0	-2.2 (-2.7)	1.9	8.9	---	--	--	1.8^j
	$.1^d$	0.0	0.0	-2.2 (-2.7)	1.9	8.9	---	--	--	1.8^j
	0.0	$.5^h$	0.0	-2.2 (-2.7)	1.9	8.9	2 (-1.3)	2.7	9.7	1.8^j

Table 1 - Continued

Special Costs/Yr. ($1,000)		Use for Waste Btu ($1,000 @ $4/Btu 10^6)		Net System Costs & Benefits ($1,000/yr.)						Special Savings ($1,000/yr)
Sealed Manure Pit	Residue Lagoon	Greenhouse Heat	Manure Drying For Refeed	Energy replacement & Fertilizer Enrichment only (Energy only)	Energy & Refeed Value $23	Energy & Refeed Value $90	Energy, Fertilizer & Foil Waste Heat Use 70% (energy & heat only)	Energy, Refeed & 40% Use of Waste Heat[l] $23	Energy, Refeed & 40% Use of Waste Heat[l] $90	Manure Disposal
0.0	0.0	0.0	0.0	-.7 (-1.3)	.8	5.1	---	--	--	.65
0.0	0.0	1.1	0.0	-.1 (-1.3)	2.8	11.3	.6 (-.6)	3.2	11.7	1.3
0.0	1.1	3.7	3.7	-.6 (-7.3)	.4	45.1	2.0 (-4.7)	1.9	46.6	3.3
0.0	0.0	1.5	1.5	-4.3 (-5.8)	-1.7	9.0	-3.3 (-4.8)	-1.1	9.6	.25
0.0	1.2[o]	4.6	4.6	-.8 (-5.8)	-9.5	24.8	2.4 (-2.6)	-7.6	26.7	.81
0.0	0.0	1.8	0.0	-4.4 (-6.0)	-2.1	9.0	-3.1 (-4.7)	-1.4	9.7	.26
0.0	1.2[o]	4.6	4.6	.2 (-4.8)	-6.9	29.9	3.4 (-1.6)	-5.1	31.7	.80
0.0	0.0	1.8	0.0	-4.4 (-6.1)	-1.5	10.4	-3.1 (-4.8)	-.8	11.1	.28
0.0	3.2[o]	11.4	11.4	14.3 (-2.5)	17.3	105.0	18.5 (5.5)	21.9	109.6	2.1

i. Manure disposed of as refeed; standard manure spreader used.
j. Limited to systems where manure is disposed of as refeed. Assumes use of liquid manure spreader at rate of 8.2 hr./mo.
k. Assumes effluent is twice volume of influent.
l. Assumes greenhouse heat only.
m. Assumes refeeding takes place on site and requires no dewatering.
o. Assumes 3-month storage of residue + cost of pump.
p. Assumes 3-month storage of feedstock + cost of pump.

Table 2
Financial Feasibility of Anaerobic Digestion Systems
on Livestock and Poultry Farms in Leading Producer States

Livestock	Total Investment ($1,000)			Income Tax Credit/Yr. ($1,000)		Insurance Cost/Yr. ($1,000)	
State Avg. No. Sold per farm (Inventory)	With Dewatering Equipment	Without Dewatering Equipment	Added Labor Cost ($1,000/Yr.)	With Dewatering Equipment	Without Dewatering Equipment	With Dewatering Equipment	Without Dewatering Equipment
Turkeys							
Minnesota							
124,000	345.5	227	15.0	14.5	9.5	1.7	1.1
California							
98,000	290	191	15.0	12.1	8.0	1.5	1.0
No. Carolina							
89,000	286	187	15.0	12.0	7.9	1.4	.9
Broilers							
Minnesota							
52,000	---	31			1.3		.2
198,000	166	106		7.0	4.5	.8	.5
California							
56,000	---	30			1.3		.2
1,377,000	308	190	15.0	12.9	8.0	1.5	1.0
Arkansas							
63,200	---	45			1.9		.2
186,000	136	84		5.7	3.5	.7	.4
Swine							
Iowa							
1,600		42			1.8		.2
Missouri							
1,600		42			1.8		.2
No. Carolina							
1,600		42			1.8		.2

Table 2 - Continued

Livestock State Avg. No. Sold per farm (Inventory)	Total Investment ($1,000)		Added Labor Costs ($1,000/Yr.)	Income Tax Credit/Yr. ($1,000)		Insurance Cost/Yr. ($1,000)	
	With Dewatering Equipment	Without Dewatering Equipment		With Dewatering Equipment	Without Dewatering Equipment	With Dewatering Equipment	Without Dewatering Equipment
Dairy Cows							
Wisconsin							
(32)		26			1.1		.1
New York							
(64)		26			1.1		.1
California							
(337)	161	101		6.8	4.2	.8	.5
Laying Hens							
Minnesota							
(12,922)	---	56			2.4		.3
(41,405)	173	90		7.3	3.8	.9	.4
Georgia							
(13,500)		56			2.4		.3
(40,800)	173	90		7.3	3.8	.9	.4
California							
(14,300)		56			2.4		.3
(105,200)	273	164	15.0	11.5	6.9	1.4	.8

Table 2 - Continued

Livestock State Avg. No. Sold per farm (Inventory)	Overall Costs and Returns ($1,000/Yr.)							
				Energy and Fertilizer Enrichment	Energy, Fertilizer Enrichment 70% Waste Heat Use		Energy, Refeed and 40% Use of Waste Heat	
	Energy Only	Energy & Refeed @ $29/Ton	Energy & Refeed @ $90/Ton	@ $10/dry ton value added	All	Energy Only	@ $23/dry ton	@ $90/dry ton
Turkeys								
Minnesota								
124,000	23.4	47.8	131.8	33.9	40.9	28	45.3	129.3
California								
98,000	1.3	18.6	85.3	12.4	16.2	6.5	19.8	87
No. Carolina								
89,000	4.3	6.6	75.6	2.8	4.9	-3.5	9.8	79
Broilers								
Minnesota								
52,000	-.4	1.2	4.8	-.3	---	---	---	
198,000	.6	-3.2	10.3	1.7	---	---	---	
California								
56,000	-.3	6.1	9.7	.3	.8	.2	1.7	5.3
1,377,000	30.9	-4.9	8.1	32.5	38.9	30.1	1.3	91.7
Arkansas								
63,200	-2.7	-.7	3.5	-2.1	-1.3	-1.9	-.3	2.1
186,000	1.6	-.3	12.2	3.5	4.5	2.6	.3	12.8
Swine								
Iowa								
1,600	-1	3.5	10.5	0				
Missouri								
1,600	-1	3.5	10.5	0				
No. Carolina								
1,600	-.6	3.5	10.5	0	3.8	.3	3.9	10.9

Table 2 - Continued

Livestock State Avg. No. Sold per farm (Inventory)	Overall Costs and Returns ($1,000/Yr.)							
	Energy Only	Energy & Refeed		Energy and Fertilizer Enrichment	Energy, Fertilizer Enrichment 70% Waste Heat Use		Energy, Refeed and 40% Use of Waste Heat	
		@ $29/Ton	@ $90/Ton	@ $10/dry ton value added	All	Energy Only	@ $23/dry ton	@ $90/dry ton
Dairy Cows								
Wisconsin								
(32)	-.3	1.8	6.1	.3				
New York								
(64)	-.3	3.8	12.3	.9	1.6	.4	4.2	127
California								
(337)	-3.7	6.5	51.2	2.9	5.5	-1.2	8.0	52.7
Laying Hens								
Minnesota								
(12,922)	-3.9	.3	11.0	-2.1	-1.3	-2.8	.9	11.6
(41,405)	-2.5	-3.3	31.0	2.6	5.6	.8	-1.4	32.7
Georgia								
(13,500)	-4.0	-.1	11.0	-2.2	.0	3.1	.6	11.7
(40,800)	-2.0	-.7	38.1	3.8	16.0	1.8	1.1	39.9
California								
(14,300)	-4.1	.5	12.4	-2.2	-1.1	-2.8	1.2	13.1
(105,200)	-11.8	12.4	107.3	.8	.8	-4.0	17.0	104.1

GAS RECOVERY FROM MSW - SEWAGE SLUDGE ANAEROBIC DIGESTERS

Joseph T. Swartzbaugh, Ph.D.
Catherine E. Jarvis*
Ralph B. Smith
Systems Technology Corporation
245 North Valley Road
Xenia, Ohio 45385

ABSTRACT

The anaerobic digestion of the light organic fraction of municipal solid waste was studied on a full-scale 100,000 gallon digester. Based on earlier studies which showed that normal wastewater treatment mixing was inadequate for digestion of MSW, two mixing modes, a mechanical agitator, and a gas draft tube agitator were alternately employed and evaluated at various MSW:sewage sludge ratios and loading rates, with total solids from 4 to 10 percent. The results of these studies indicate that materials handling problems associated with the slurried refuse will restrict the use of this technology for energy recovery.

INTRODUCTION

Anaerobic digestion has a long history of use in treatment of sewage sludge. However, application of this technology to biogasification of municipal solid waste (MSW) presents several difficulties due to the nature of the feed. The cleaned organic fraction of MSW is composed largely of cellulose. It's susceptibility to microbial degradation is determined by accessibility of the cellulose to enzymes, which requires direct contact between enzyme and substrate. Cellulose is largely water insoluble and is composed of long chains of glucose units linked by $\beta 1,4$ bonds aggregated into bundles of microfibrils. The microfibrils contain amorphous regions which are rapidly hydrolyzed during biodegradation, and highly ordered crystalline regions, which are of restricted accessibility to enzymes and limit the rate of degradation. Waste cellulose materials contain 40 to 60 percent cellulose plus hemicellulose and lignins. The degree of lignification also affects the breakdown of cellulosic materials by shielding the cellulose substrate.

In addition to the chemical properties of crystallinity and lignification of cellulose, the physical behavior of the material in an agitated slurry is also relevant to anaerobic digestion of MSW. Cellulose fibers tend to float on the surface of the liquid and adhere to one another on contact during mixing, forming increasingly larger mats of fibrous scum.

One other component of municipal solid waste-derived feeds for anaerobic digestion which must be dealt with is grit. Even though the light organic fraction of the waste has had the majority of glass and metal removed, a significant amount of ground glass, sand, and grit remains in the feed, the abrasive nature of which requires consideration during design and operation.

The properties of municipal solid waste are significantly different from sewage sludge. Thus the direct application of anaerobic digestion, as practiced in wastewater treatment, is not feasible. This paper presents the results of the first full-scale studies of this technology and discusses the technical implications for future applications.

---

* Now at Pedco Environmental, Inc.; Cincinnati, Ohio

HISTORY OF THE PROJECT

In 1974 through 1975, a laboratory and full-scale study by EPA was conducted to evaluate the feasibility of converting municipal solid waste and sewage sludge mixtures to methane anerobic digestion. The light organic fraction of hydropulped municipal solid waste was combined with sewage sludge from a municipal wastewater treatment plant. Two 55 gallon laboratory digesters were operated at several MSW to raw sludge ratios and volatile solids loading rates. The results of these studies indicated that the material tends to accumulate as a fibrous mat on top of the digester. Following the laboratory studies, a pilot study was performed in the 35 foot (10.7 m) diameter, 100,000 gallon (387,500 ℓ) digester. After 75 days of operation, the pilot scale study was terminated due to the formation of a 2 to 5 foot scum layer at the top of the digester. Both of these studies indicated that one of the most important operational parameters for successful digestion of MSW to sludge blends is adequate mixing of the contents.

CURRENT STUDY

The current study is being performed in order to test and compare two methods of mixing; a mechanical agitator mounted in the center of the tank, and three gas mixing units located inside the digester in an equilateral triangle at approximately half the radius of the vessel. A series of experiments were conducted using two loading rates and two blends of organic components derived from MSW and sewage sludge according to the outline shown in Table 1.

The digester vessel is equipped with a Chemineer Model 4HTD10 10 hp mechanical mixer with 54 inch (1.4 m) agitator blades, an Aerohydraulics Model 3-12 "expanding piston" type 5 hp gas mixer with three draft tubes and a Vaughan Model 300 "Scum Buster" 40 hp scum breaker pump. A 20 hp 1L12H-CDR Moyno pump is used for feeding and releasing effluent from the digester. During each study, either the mechanical agitator or the gas mixers were operated at all times except during sampling. The scum breaker pump was used during startup of a study to prevent scum accumulation prior to data collection, between studies to break up the scum layers, and during studies if the scum build-up was excessive. "Scum Buster" use during a study is noted in the results section.

Figure 1 shows the locations of the mixing equipment and sampling ports. The sampling ports are numbered from 1 to 6, with samples taken from each port at three levels (top, middle, and near bottom). Samples are referenced with the port number followed by the level at which it was taken, thus solids at 1-3 are from sampling port 1, level 3 (bottom level).

Monitoring

The objective of this study is to evaluate mixing methods, therefore, the most important monitoring parameter is solids distribution within the digester. There are 6 sampling ports on the digester cover. The digester contents are sampled bi-weekly at three depths in each port in order to monitor scum formation and solids distribution within the vessel. The monitoring schedule also includes daily gas production, feed solids, and analyses of the effluent for pH, alkalinity, volatile acids, total solids, and volatile solids. Volatile acids and alkalinities are performed, also bi-weekly, on 6 of the samples from the ports. These analyses provide a profile of the conditions within the digester according to location. In addition, a weekly gas chromatographic analysis is performed, and nitrogen and phosphorous analyses of the feeds are determined in order to calculate the supplemental nutrient requirements of the digester.

RESULTS

First Study: Gas Mixing (3:1, 0.08, 4% TS)

The results of the first gas mixing study using a 3:1 ratio of municipal solid waste to sewage sludge at a loading rate of 0.08 pounds (1.25 gm/ℓ) of volatile solids per cubic foot per day are shown in Tables 2 and 3. The numbers shown in these figures represent a time history of the values obtained throughout the gas mixing study. The data reflect conditions during use of the scum breaker pump. It was intended that the "Scum Buster" be used during the first retention time of the study and not afterward during data collection. However, the motor on the gas mixing system compressor required replacement (due to a faulty motor), and in the interest of continuing the project, the data already collected was used.

Tables 2 and 3 show that the solids in the top layer of the digester are higher than the solids in the middle or bottom of the vessel. In addition to the actual values being slightly higher, the standard deviation of these values is also greater. During the course of the study, it was noticed that there was a cohesive mass of floating material moving within the top layer of the digester. Throughout the course of the study, this mass of material was sampled at 1 to 3 ports per sampling, resulting in higher average values for the total solids in level 1. This is the reason for the high mean values as well as the high standard deviation of these numbers at level 1. Gas production during this study averaged approximately 5,000 cubic feet (141,600 ℓ) per day. The volatile acids to alkalinity ratio averaged approximately .4 to .5. Gas composition was generally 70 percent methane and 25 percent carbon dioxide. The feed blend contained 4.1 percent total solids, the effluent average was 3.2 percent total solids. The calculated volatile solids destruction was 48 percent.

Second Study: Mechanical Mixing (3:1, 0.08, 4% TS)

Tables 4 and 5 summarize solids distribution results for the first mechanical mixing study operated at a 3:1 refuse:sludge ratio of 4 percent total solids and 0.08 pounds VS/ft^3/day loading rate. The total solids in the beginning of the study were relatively uniform with an average of 4.5 percent TS in the top level. After one week the samples taken from port 1 showed high solids of 10 percent. Within two weeks, samples from two of the ports were high in total solids, but the remaining ports were still similar to the samples taken from levels 2 and 3. Within three weeks, an extensive 2-foot thick scum layer averaging 25 percent TS existed in the vessel. By four weeks, the scum layer was 3 to 5 feet thick at ports 5 and 6, closest to the wall, and was dry and hard on the top. Scum at port 4 was 1 foot thick and also drying. Samples taken from ports 1 and 2 nearest the mechanical agitator indicated a soft 1 foot scum layer at those locations. As in the first study, high total solids correspond to high volatile solids which are the substrate for the microorganisms, thus an increasingly larger amount of food becomes tied up in the floatable layer.

Visual inspection of the contents through the sampling ports revealed further information about the type and extent of mixing within the digester. The top layer was moving around the vessel (rotating about the shaft of the center-mounted agitator). The only place where the movement was turbulent was near the shaft. The movement was markedly slower near the walls of the digester. According to the manufacturer of the mechanical agitator, the type of mixing expected for the power of the motor, size of the blades, and length of the shaft installed in the digester is generally axial flow within the body of the fluid with a radial component at the level of the blades, and slow surface motion without uniform lifting of solids to the top layer. This is the type of mixing which the data and visual observation indicate is the case. In order to obtain uniform or near-uniform distribution of solids, a much larger horsepower motor would have to be used, 75 hp rather than 10 hp, according to the manufacturers recommendations. The smaller power motor was chosen in order to be comparable to the power of the gas mixer compressor (5 hp). Use of the 75 hp motor would also have consumed unduly large amounts of energy which is not desirable in an energy-recovery process.

The mixing conditions consisted of continual use of the mechanical agitator and the recirculating pump with a 4 to 24 hours per day use of the "Scum Buster" pump. Initially, the study was run with continuous use of the scum breaker pump, this was decreased to 4 hours per day when results were satisfactory in order to evaluate the mechanical agitator, however, this was gradually increased to continuous operation again as the scum layer accumulated. The last set of data entered in Figures 4 and 5 reflect conditions after using the "Scum Buster" 24 hours per day.

Despite the accumulation of floatable material within the vessel, the digester was performing satisfactorily. Gas production during this study averaged approximately 6,660 cubic feet per day. The volatile acids to alkalinity ratio varied from 0.1 to 0.3. Gas composition was generally 60 percent methane and 35 percent carbon dioxide. The feed blend averaged 4.62 percent total solids. The calculated volatile solids destruction was 49 percent. Gas production averaged 12.9 ft^3 per pound of volatile solids destroyed. These parameters indicate improved performance compared to the first study. This is most likely attributable to the fact that the digester had time to adapt to the feed and become more stable.

Third Study: Gas Mixing (3:1, 0.15, 4% TS Feed)

Tables 6 and 7 show solids distribution during the gas mixing study at the higher loading rate. A scum layer of 20 percent or more solids existed in the digester within a short period of time. The scum layer, consisting mostly of fibrous material, became 1 foot thick after a few weeks, and was approximately 2 feet thick at the end of two months. By the end of the study, the top of the scum was becoming dry, indicating little if any, turnover of the material. The solids data show a relatively well-mixed digester below the scum layer, although the major portion of the substrate was held in the scum layer, as shown by the low total and volatile solids in the rest of the digester. The scum breaker pump was not used during this study so that effectiveness of the gas mixing system alone could be monitored.

The volatile acids to alkalinity ratio during this study was 0.6 to 0.8, signifying digester difficulty, probably due to the high loading rate. However, the ratio decreased with time indicating some adaptation to the high loading. Gas production in the beginning of the study increased to 8,000 ft^3 per day, however, it was not measured during the rest of the study due to meter freezing problems, therefore, the gas production per pound of volatile solids destroyed is not available.

Fourth Study: Gas Mixing (9:1, 0.08, 4%, TS Feed)

The first line of data in Table 8 indicates conditions in the digester before the study actually began after use of the scum breaker pump. The total and volatile solids were uniform throughout the vessel except at level 1 of port 5, which is located along the wall. The next few sets of data show increasingly higher solids at level 1. The scum layer seemed to spread from the wall to the center. Within a week, the scum layer extended over most (if not all) of the surface, and averaged 18 percent total solids.

As in the other studies, high total solids correspond to high volatile solids. Although the study was not complete, early data showed a volatile solids reduction of 47 percent. Volatile acid to alkalinity ratios averaged 0.3 indicating a favorable balance between the acid and methane forming groups.

Fifth Study: Mechanical Mixing (9:1, 0.08, 4% TS Feed)

Tables 10 and 11 indicate that an exceedingly rapid build-up of solids at the upper level occurs near the walls. A gradual increase in solids with time does occur at port 3, but throughout the period of the study, ports 1 and 2 show no scum build-up at the upper levels. Again, the total solids in the well-mixed region show an exceedingly low total solids concentration. Also, the volatile solids concentrations appear to indicate that the solids in the well-mixed region are low in volatiles as compared with the solids in the entrapped region. This again corroborates our belief that the cellulosics are being rapidly captured and removed from the actively-mixed region, and thus are not available for degradation.

Sixth Study: Mechanical Mixing (9:1, 0.14, 7% TS Feed)

As indicated in Tables 12 and 13, the total solids distribution shows that ports 1 and 2 remain clear. However, the solids accumulation is such that ports 3, 4, and 5 each show an exceedingly high solids concentration at the upper levels, meaning that the material in the scum layer is continually drying. Toward the end of the study, the material in the scum layer can be seen to be sufficiently dry to support combustion. In fact, at some points in the study, it was impossible to break into the scum layer at port 4 to withdraw a sample. As before, the volatile solids concentration appears to be higher in the unmixed region, while the total solids concentration is exceedingly low in the well-mixed portion of the digester. Even though the feedstock is entering the digester at 7 percent total solids, the digester contents in the well-mixed region appear to be around 1 percent and rarely higher than 2 percent total solids. What this means is that the solids are immediately being removed from the well-mixed area and immediately adding their bulk to the scum layer.

Seventh Study: Gas Mixing
(9:1, 0.14, 7% TS Feed)

Indications from the data in Tables 14 and 15 are that the gas mixing system does allow an accumulation of solids throughout the upper region of the digester. While the solids in the center portion of the digester do not achieve the levels seen in the outer regions of the digester, still the samples taken from the top level show an unmistakable accumulation of solids. Again, the total solids in the lower regions of the digester appear to be about 1 percent total solids. It is interesting to note that the scum layer had become so dense and so dry that it was physically impossible to break through the scum layer at ports 3 and 4 to obtain samples from the lower regions. Analysis of the materials drawn from ports 1, 2, and 5, however, indicate that the digester contents are still well mixed in those regions while the total solids again appear to be fairly constant at about 1 percent.

Eighth Study: Gas Mixing
(9:1, 0.20, 10% TS Feed)

Again, the gas mixing system noticeably allowed an increase in the solids accumulation at the upper levels of the digester. In spite of the fact that the solids content in the feed had been increased to an average of 10 percent, the solids content in the levels 2 and 3 of the digester indicate the self-limiting characteristic that we have noticed earlier so that the total solids in these regions tend to stay at about 1 percent.

Ninth Study: Mechanical Mixing
(0:1, 0.20, 10% TS Feed)

The mechanical agitating system did again succeed in keeping the solids reduced in the upper levels near the center of the digester. It is noticeable that the total solids concentration in the well-mixed region is slightly higher than has been seen before, undoubtedly due to the fact that the total solids concentration in the feedstock is so high. As before, the total solids throughout the rest of the digester, though appearing to be well-mixed, indicate that the digester contents in the active region are about 1 to 2 percent total solids.

CONCLUSIONS

Based on the results of this study, it is our contention that it is impossible to properly agitate a feedstock of higher than approximately 5 percent total solids utilizing agitation technology as it has been commonly applied for wastewater treatment. The feedstock of gritty, cellulosic material typical of municipal solid waste is not amenable to any form of low energy agitation. The intent of anaerobic digestion of MSW is energy recovery, and this particular technology does not result in a high energy recovery efficiency. The best that can be expected is 60 to 70 percent of the volatile solids being converted into a recovered energy product (CH_4). Furthermore, the process utilizes approximately 50 percent of the carbon in that converted portion for producing carbon dioxide, which is of no value as an energy product. For this reason, we feel that the process must be restricted to low energy agitation.

Furthermore, the gritty content of the material is exceedingly difficult to remove, and probably can never be fully removed. This does result in extreme operating problems for any equipment whose moving parts are exposed to this material. The Moyno pump utilized in this study was operated in several configurations, finally with a rubber stator and chrome plated rotor. Even in this configuration, the operating life time of the Moyno pump is on the order of 30 to 40 days. The "Scum Buster" Pump experienced severe damage throughout the study. It was necessary to remove the "Scum Buster" Pump three times for repair, and at the end of the study, it was discovered that it had effectively disintegrated within the digester. Twice the cutter bar and bottom plate assembly fell off the "Scum Buster" and have not been retrieved.

The inspection of the mechanical agitator system at the completion of the studies indicated an exceedingly large build-up of cellulosic material. This material appears to have adhered to itself, and formed long rope-like stringers, which then became wound around the shaft of the mechanical agitator. It appears that the action is quite similar to the action of a spinning wheel in that the fibrous material tends to adhere to itself and gradually get wrapped and twisted into threads which rapidly accumulate. This accumulation is so great that either regular removal of the material must be effected or the cellulosic material will accumulate to such an extent that the hub of the shaft would be as large in diameter as the agitator blades themselves so that, in effect, no mixing at all would occur. Furthermore, this accumulated material causes a tremendous strain on the mechanical agitator drive mechanism (see Figure 2). Obviously it does not accumulate in any well-balanced manner and so the agitator drive mechanism is constantly trying to turn an ever heavier and ever more unbalanced shaft. This results in extreme wear at the gas seal bearing, and makes it exceedingly difficult to maintain a gas tight digester. It is our contention, as a result of this study, that bioconversion of municipal solid waste utilizing the concept of a well-mixed anaerobic digester is not a feasible approach to energy recovery.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the contributions of Messrs. Robert J. Griffin, James Thomas, Gerald Ellis, and Jeff McNiece for the daily operation of the digester facility.

LIST OF TABLES

Table Number	Description
1	Summary of Operating Conditions
2	Total Solids Distribution for Study 1
3	Volatile Solids Distribution for Study 1
4	Total Solids Distribution for Study 2
5	Volatile Solids Distribution for Study 2
6	Total Solids Distribution for Study 3
7	Volatile Solids Distribution for Study 3
8	Total Solids Distribution for Study 4
9	Volatile Solids Distribution for Study 4
10	Total Solids Distribution for Study 5
11	Volatile Solids Distribution for Study 5
12	Total Solids Distribution for Study 6
13	Volatile Solids Distribution for Study 6
14	Total Solids Distribution for Study 7
15	Volatile Solids Distribution for Study 7
16	Total Solids Distribution for Study 8
17	Volatile Solids Distribution for Study 8
18	Total Solids Distribution for Study 9
19	Volatile Solids Distribution for Study 9

LIST OF FIGURES

Figure Number	Description
1	Representation of the Digester Showing Location of Mixing Equipment and Sampling Ports.
2	View of the Digester Interior After 245 Days of Operation. (NOTE: The person shown is standing atop a four-foot thick blanket of accumulated, undigested feed.)

SUMMARY OF OPERATING CONDITIONS

Mixing Mode	Feed Ratio (MSW:Sewage Sludge)	Loading Rate (# Volatile Solids/ ft^3/day)	Total Solids In Feed (%)
1. Gas	3:1	0.08	4
2. Mechanical	3:1	0.08	4
3. Gas	3:1	0.15	4
4. Gas	9:1	0.08	4
5. Mechanical	9:1	0.08	4
6. Mechanical	9:1	0.14	7
7. Gas	9:1	0.14	7
8. Gas	9:1	0.20	10
9. Mechanical	9:1	0.20	10

TOTAL SOLIDS DISTRIBUTION FOR STUDY 1
(Gas Mixing, 3:1, 0.08, 4% TS Feed)

Level	Date	Percent Total Solids by Port Number				
		5 (wall)	4	3	2	1 (center)
Top	8/01	6.14	8.68	3.87	7.15	1.93
	8/04	6.01	6.29	4.38	4.35	3.23
	8/08	3.92	3.88	3.16	4.73	3.04
	8/11	2.48	10.29	5.55	2.54	2.04
	8/15	9.52	3.21	4.21	3.25	2.83
	8/18	12.52	3.45	3.27	4.20	2.66
	8/22	9.62	13.21	10.44	6.59	5.26
	8/25	5.55	5.50	5.56	7.94	11.41
Middle	8/01	2.98	2.69	2.99	2.92	2.62
	8/04	3.64	3.84	6.40	3.93	2.43
	8/08	2.81	3.29	4.83	3.23	3.00
	8/11	3.48	3.65	2.19	2.30	2.53
	8/15	3.25	2.76	2.76	2.65	2.80
	8/18	2.41	2.54	2.47	2.30	2.58
	8/22	3.47	5.30	4.55	2.83	3.57
	8/25	2.64	3.36	2.80	3.21	3.08
Bottom	8/01	2.40	2.54	1.82	2.77	2.92
	8/04	5.28	4.20	--	4.43	3.75
	8/08	3.72	4.84	3.94	3.06	3.30
	8/11	0.93	1.62	3.11	2.89	6.02
	8/15	--	5.00	3.48	3.77	3.46
	8/18	3.60	4.69	2.50	3.88	2.80
	8/22	4.13	3.35	3.14	5.42	3.37
	8/25	3.12	2.91	3.27	3.63	3.14

VOLATILE SOLIDS DISTRIBUTION FOR STUDY 1
(Gas Mixing, 3:1, 0.08. 4% TS Feed)

Level	Date	Percent Volatile Solids by Port Number				
		5 (wall)	4	3	2	1 (center)
Top	8/01	63.1	64.1	64.0	65.7	83.7
	8/04	57.4	55.0	49.1	47.4	54.7
	8/08	53.3	51.5	52.6	59.8	48.7
	8/11	53.7	62.5	58.4	57.9	54.0
	8/15	61.0	52.8	60.6	51.9	56.0
	8/18	62.1	56.7	56.2	55.9	52.0
	8/22	62.3	61.0	54.9	61.7	55.6
	8/25	54.3	56.6	56.7	59.3	56.2
Middle	8/01	76.2	60.4	59.1	61.6	56.6
	8/04	50.0	53.5	54.5	53.2	56.5
	8/08	67.7	53.1	55.4	52.2	48.4
	8/11	51.9	47.6	44.4	48.5	51.0
	8/15	51.6	53.2	50.9	48.0	52.1
	8/18	51.5	52.4	52.5	52.5	51.4
	8/22	56.2	57.3	52.6	48.6	54.7
	8/25	48.8	47.4	52.2	47.8	50.0
Bottom	8/01	75.0	58.6	79.6	57.7	69.4
	8/04	56.2	54.6	--	48.8	47.4
	8/08	61.7	57.1	53.0	42.4	47.5
	8/11	66.1	60.0	48.0	51.4	50.5
	8/15	--	52.2	50.0	52.1	51.6
	8/18	50.5	58.4	50.6	52.0	50.0
	8/22	51.0	54.2	58.9	49.3	50.5
	8/25	49.3	53.4	58.5	51.6	52.9

TOTAL SOLIDS DISTRIBUTION FOR STUDY 2
(Mechanical Mixing, 3:1, 0.08, 4% TS Feed)

Level	Date	Percent Total Solids by Port Number				
		5 (wall)	4	3	2	1 (center)
Top	8/29	4.80	3.94	5.62	3.77	4.22
	9/01	8.07	3.37	3.98	6.51	3.95
	9/05	3.79	4.81	5.63	5.00	10.11
	9/08	4.70	4.14	4.01	4.17	3.57
	9/12	4.61	11.35	5.03	3.62	3.51
	9/15	16.02	13.77	11.87	8.74	7.99
	9/19	27.13	24.62	24.20	20.49	27.67
	9/22	26.56	23.05	14.26	23.19	22.51
	9/26	27.31	18.54	19.06	11.36	7.77
	9/29	21.49	25.03	31.05	22.09	19.94
Middle	8/29	3.80	4.57	3.44	3.91	2.00
	9/01	3.25	4.26	3.39	3.32	1.95
	9/05	4.85	3.45	4.12	5.18	5.56
	9/08	3.79	3.87	3.82	3.78	3.85
	9/12	4.52	3.70	3.87	3.33	3.67
	9/15	3.75	3.34	3.44	3.83	3.42
	9/19	3.41	3.10	2.36	2.92	3.17
	9/22	3.55	3.51	3.46	3.97	3.74
	9/26	4.23	2.86	3.15	3.46	2.94
	9/29	3.16	3.20	3.73	3.25	3.31
Bottom	8/29	3.46	3.56	3.18	3.62	3.61
	9/01	3.34	6.27	--	3.64	3.49
	9/05	4.61	3.85	3.18	3.60	3.26
	9/08	3.83	3.23	3.82	3.62	4.72
	9/12	4.58	3.29	3.45	3.70	3.69
	9/15	3.82	3.39	3.36	5.17	3.23
	9/19	3.12	3.91	3.40	3.91	3.40
	9/22	3.22	3.26	4.00	3.27	3.23
	9/26	3.03	3.16	3.00	2.26	3.95
	9/29	2.96	3.30	3.13	3.38	3.26

VOLATILE SOLIDS DISTRIBUTION FOR STUDY 2
(Mechanical Mixing, 3:1, 0.08, 4% TS Feed)

Level	Date	Percent Volatile Solids by Port Number				
		5 (wall)	4	3	2	1 (center)
Top	8/29	55.6	55.3	57.4	54.6	55.7
	9/01	68.5	50.9	56.0	61.0	58.0
	9/05	55.1	55.5	56.2	55.9	59.8
	9/08	60.7	57.6	58.3	55.5	52.1
	9/12	53.7	63.7	54.0	50.5	--
	9/15	73.1	78.3	71.0	65.5	69.1
	9/19	67.3	71.2	69.7	70.0	71.1
	9/22	67.5	75.7	73.1	68.3	76.8
	9/26	72.0	75.3	78.9	71.4	68.9
	9/29	71.0	75.0	76.3	74.5	75.4
Middle	8/29	53.9	57.3	48.8	51.0	50.0
	9/01	50.9	61.3	51.8	46.9	46.1
	9/05	53.2	49.5	50.9	53.2	53.9
	9/08	55.5	54.8	56.0	51.5	53.8
	9/12	51.8	46.7	51.9	54.6	46.8
	9/15	50.5	50.6	49.4	50.9	46.0
	9/19	47.7	42.0	43.2	47.0	48.5
	9/22	51.7	59.1	55.4	43.1	42.3
	9/26	53.7	50.0	51.4	50.5	52.6
	9/29	53.9	47.4	45.7	47.1	48.8
Bottom	8/29	52.4	50.0	49.4	48.8	50.6
	9/01	54.7	75.6	41.1	51.0	54.2
	9/05	50.9	47.5	51.1	52.4	50.6
	9/08	54.2	54.2	55.2	56.9	53.3
	9/12	52.8	48.6	46.8	52.6	52.5
	9/15	52.3	52.7	47.8	71.7	48.9
	9/19	45.0	49.0	41.7	48.0	50.0
	9/22	51.2	52.7	58.4	41.6	40.9
	9/26	43.0	51.1	50.5	21.1	42.2
	9/29	46.7	46.0	45.0	47.6	45.8

TOTAL SOLIDS DISTRIBUTION FOR STUDY 3
(Gas Mixing, 3:1, 0.15, 4% TS Feed)

Level	Date	Percent Total Solids by Port Number				
		5 (wall)	4	3	2	1 (center)
Top	11/28	5.4	5.0	4.1	3.1	3.9
	01/16	22.8	--	26.7	22.0	21.8
	01/19	22.1	23.8	22.3	18.3	16.5
	01/23	19.7	17.7	21.7	22.2	18.9
Middle	11/28	3.9	3.5	4.7	2.1	3.4
	01/16	4.5	--	4.4	9.3	7.3
	01/19	1.6	1.9	5.7	2.5	5.3
	01/23	1.7	1.8	2.0	1.8	2.5
Bottom	11/28	3.9	3.4	3.4	3.8	5.0
	01/16	7.3	--	4.3	10.4	3.7
	01/19	1.3	3.1	2.0	4.3	1.2
	01/23	2.9	1.6	3.4	3.0	3.4

VOLATILE SOLIDS DISTRIBUTION FOR STUDY 3
(Gas Mixing, 3:1, 0.15, 4% TS Feed)

Level	Date	Percent Volatile Solids by Port Number 5 (wall)	4	3	2	1 (center)
Top	1/16	61.6	--	65.9	56.8	56.7
	1/19	65.7	60.8	62.6	59.8	68.9
	1/23	83.7	68.4	66.7	67.1	73.4
Middle	1/16	48.1	--	52.5	49.5	44.0
	1/19	46.7	45.8	53.8	43.1	51.3
	1/23	48.1	53.1	53.2	50.0	54.0
Bottom	1/16	48.1	--	49.6	49.5	--
	1/19	44.4	50.0	45.9	49.5	43.3
	1/23	44.2	51.1	43.9	48.2	46.7

TOTAL SOLIDS DISTRIBUTION FOR STUDY 4
(Gas Mixing, 9:1, 0.08, 4% TS Feed)

Level	Date	Percent Total Solids by Port Number				
		5 (wall)	4	3	2	1 (center)
Top	3/23	21.5	1.3	2.0	2.0	1.9
	3/27	19.0	17.8	3.6	2.3	18.6
	3/30	15.2	22.7	14.8	15.6	17.1
	4/03	18.9	17.7	20.1	14.2	19.4
	4/06	18.5	13.8	21.2	17.6	18.1
	4/10	15.1	16.1	15.0	20.0	15.2
	4/13	12.6	13.4	14.6	16.5	16.6
Middle	3/23	2.5	1.9	1.9	1.9	1.8
	3/27	1.7	1.4	1.7	1.5	1.8
	3/30	1.6	1.6	1.3	1.3	1.7
	4/03	0.9	0.9	1.1	1.5	1.7
	4/06	1.3	1.1	1.1	1.0	1.1
	4/10	0.9	0.9	0.4	0.8	0.5
	4/13	0.6	0.5	0.7	0.7	0.6
Bottom	3/23	3.2	1.9	1.9	2.4	2.2
	3/27	1.7	1.6	1.8	2.0	3.3
	3/30	1.5	1.5	1.3	1.6	1.8
	4/03	1.1	0.9	1.3	1.4	2.3
	4/06	1.0	0.9	1.2	1.0	1.2
	4/10	0.5	2.4	0.9	1.7	0.5
	4/13	0.8	0.5	0.8	1.9	1.1

VOLATILE SOLIDS DISTRIBUTION FOR STUDY 4
(Gas Mixing, 9:1, 0.08, 4% TS Feed)

Level	Date	Percent Volatile Solids by Port Number				
		5 (wall)	4	3	2	1 (center)
Top	3/23	71.3	36.4	53.6	56.0	53.1
	3/27	70.6	61.3	59.7	58.9	71.1
	3/30	61.3	64.3	79.3	67.8	76.2
	4/03	59.0	72.3	71.5	74.0	78.2
	4/06	65.5	68.6	68.3	70.8	--
	4/10	64.7	69.5	65.0	79.0	73.3
	4/13	68.9	68.5	68.7	79.5	78.6
Middle	3/23	51.1	53.1	52.9	51.9	51.2
	3/27	45.1	50.0	45.9	41.9	45.7
	3/30	48.8	52.2	57.9	50.0	48.2
	4/03	45.0	36.8	34.5	42.4	45.7
	4/06	52.5	50.0	40.7	46.2	42.9
	4/10	62.5	55.6	70.0	53.3	53.9
	4/13	65.0	--	72.7	63.0	66.7
Bottom	3/23	55.8	53.6	54.7	63.8	50.0
	3/27	51.0	52.8	41.7	44.2	47.9
	3/30	51.1	57.1	61.8	50.0	50.9
	4/03	40.6	42.3	35.3	37.5	49.1
	4/06	43.2	37.0	46.7	41.4	43.3
	4/10	50.0	72.2	47.1	52.3	50.0
	4/13	60.1	64.7	60.9	61.3	41.7

TOTAL SOLIDS DISTRIBUTION FOR STUDY 5
(Mechanical Mixing, 9:1, 0.08, 4% TS Feed)

Level	Date	Percent Total Solids by Port Number				
		5 (wall)	4	3	2	1 (center)
Top	4/20	18.8	25.5	0.9	0.9	0.9
	4/24	17.6	27.4	0.8	0.7	1.0
	4/27	14.9	17.6	0.7	0.7	0.7
	5/02	16.9	21.0	14.8	0.4	0.5
	5/04	22.0	19.7	13.8	0.7	3.7
Middle	4/20	1.3	1.2	--	0.8	1.0
	4/24	1.3	1.7	0.6	0.6	0.5
	4/27	3.2	1.3	0.9	0.6	0.7
	5/02	0.6	0.6	0.4	0.3	0.6
	5/04	2.2	0.6	1.4	0.6	0.6
Bottom	4/20	1.5	1.3	1.3	1.3	1.0
	4/24	3.6	1.2	0.8	0.8	0.6
	4/27	1.2	2.1	0.9	0.8	0.9
	5/02	1.4	1.8	0.9	1.0	0.7
	5/04	1.3	0.9	1.4	1.7	0.8

VOLATILE SOLIDS DISTRIBUTION FOR STUDY 5
(Mechanical Mixing, 9:1, 0.08, 4% TS Feed)

Level	Date	Percent Volatile Solids by Port Number 5 (wall)	4	3	2	1 (center)
Top	4/20	65.1	69.0	36.0	40.9	44.4
	4/24	68.3	67.8	42.9	47.6	48.2
	4/27	70.7	83.6	52.0	59.1	40.0
	5/02	72.0	76.1	76.6	75.0	75.0
	5/04	72.1	69.0	62.1	43.5	69.7
Middle	4/20	40.0	40.0	--	38.1	27.8
	4/24	57.1	63.6	66.7	62.5	73.3
	4/27	79.5	47.6	44.8	42.9	39.1
	5/02	52.9	64.3	70.0	70.0	66.7
	5/04	50.9	60.0	57.6	52.6	63.6
Bottom	4/20	47.9	46.7	43.8	36.7	47.8
	4/24	50.0	68.3	61.5	69.6	66.7
	4/27	50.0	61.4	42.9	50.0	50.0
	5/02	50.0	52.3	52.6	68.0	61.1
	5/04	43.3	60.0	52.6	53.0	52.0

TOTAL SOLIDS DISTRIBUTION FOR STUDY 6
(Mechanical Mixing, 9:1, 0.14, 7% TS Feed)

Level	Date	Percent Total Solids by Port Number 5 (wall)	4	3	2	1 (center)
Top	6/05	20.7	--	30.8	1.2	0.9
	6/08	34.6	34.2	25.6	2.6	1.7
	6/12	22.1	24.6	15.0	0.9	5.9
	6/15	17.8	--	23.7	15.7	0.9
	6/19	31.6	33.9	29.3	0.7	1.3
	6/22	36.0	27.2	31.3	1.2	2.1
Middle	6/05	1.5	--	2.1	0.7	0.7
	6/08	1.1	--	2.0	0.9	1.1
	6/12	1.8	1.7	1.1	0.9	1.2
	6/15	2.5	--	1.2	3.2	0.9
	6/19	1.5	1.5	--	1.0	1.0
	6/22	1.7	1.3	--	1.3	1.3
Bottom	6/05	1.0	--	1.3	1.2	1.0
	6/08	3.8	--	1.3	1.2	0.9
	6/12	1.9	1.6	1.3	1.5	1.0
	6/15	2.8	--	1.2	0.9	0.9
	6/19	1.1	2.5	--	1.2	1.7
	6/22	2.2	1.4	--	1.2	1.7

VOLATILE SOLIDS DISTRIBUTION FOR STUDY 6
(Mechanical Mixing, 9:1, 0.14, 7% TS Feed)

Level	Date	Percent Volatile Solids by Port Number				
		5 (wall)	4	3	2	1 (center)
Top	6/05	74.5	--	64.6	71.4	46.6
	6/08	64.4	67.7	61.5	73.0	69.1
	6/12	60.8	66.0	65.5	63.3	--
	6/15	68.2	--	71.6	64.2	54.5
	6/19	56.8	66.4	59.5	60.6	59.6
	6/22	64.5	86.9	54.0	59.5	65.5
Middle	6/05	55.8	--	45.6	45.0	57.1
	6/08	65.7	--	58.0	67.8	63.1
	6/12	64.7	58.7	56.7	62.9	65.3
	6/15	54.8	--	54.5	51.4	49.4
	6/19	58.0	40.1	--	56.0	55.4
	6/22	61.7	59.0	--	57.7	56.8
Bottom	6/05	53.3	--	48.5	58.8	55.8
	6/08	39.8	--	71.4	68.6	78.9
	6/12	61.5	57.7	61.2	58.9	62.5
	6/15	57.5	--	54.8	48.8	52.0
	6/19	54.8	58.5	--	57.8	62.5
	6/22	62.3	58.3	--	58.8	60.3

TOTAL SOLIDS DISTRIBUTION FOR STUDY 7
(Gas Mixing, 9:1, 0.14, 7% TS Feed)

Level	Date	Percent Total Solids by Port Number				
		5 (wall)	4	3	2	1 (center)
Top	7/03	25.7	29.5	30.6	13.5	--
	7/06	31.0	36.5	31.3	24.4	19.9
	7/10	26.6	21.5	29.4	17.2	17.3
	7/13	31.1	35.8	35.6	28.0	17.9
	7/17	26.2	--	31.3	22.9	15.6
	7/20	33.3	37.0	35.3	18.1	16.6
Middle	7/03	2.7	--	--	1.6	1.1
	7/06	1.5	--	--	1.2	1.0
	7/10	.6	--	--	.8	.8
	7/13	1.9	--	--	2.0	1.6
	7/17	--	--	--	1.5	.8
	7/20	--	--	--	.7	.8
Bottom	7/03	2.9	--	--	1.0	1.1
	7/06	3.2	--	--	1.2	1.0
	7/10	.8	--	--	.7	.7
	7/13	1.2	--	--	1.2	1.1
	7/17	--	--	--	.9	.7
	7/20	--	--	--	.7	.7

VOLATILE SOLIDS DISTRIBUTION FOR STUDY 7
(Gas Mixing, 9:1, 0.14, 7% TS Feed)

Level	Date	Percent Volatile Solids by Port Number				
		5 (wall)	4	3	2	1 (center)
Top	7/03	74.2	62.3	47.5	76.5	--
	7/06	70.7	62.4	53.8	74.2	79.6
	7/10	58.3	55.6	55.8	73.0	74.3
	7/13	72.1	61.8	60.4	72.3	66.5
	7/17	70.0	--	48.8	--	75.9
	7/20	69.4	57.5	57.4	71.3	74.6
Middle	7/03	64.0	--	--	50.9	53.6
	7/06	56.9	--	--	54.8	52.9
	7/10	52.6	--	--	55.1	50.4
	7/13	53.2	--	--	49.3	48.6
	7/17	--	--	--	52.6	49.6
	7/20	--	--	--	53.0	54.0
Bottom	7/03	63.7	--	--	63.0	53.7
	7/06	54.6	--	--	53.5	52.9
	7/10	49.7	--	--	48.9	52.7
	7/13	55.1	--	--	58.1	73.5
	7/17	--	--	--	59.1	52.7
	7/20	--	--	--	55.9	66.6

TOTAL SOLIDS DISTRIBUTION FOR STUDY 8
(Gas Mixing, 9:1, 0.20, 10% TS Feed)

Level	Date	Percent Total Solids by Port Number				
		5 (wall)	4	3	2	1 (center)
Top	7/24	35.5	--	--	1.4	--
	7/27	29.8	35.2	35.6	14.8	--
	7/31	27.3	34.0	36.1	13.8	1.1
	8/03	32.8	33.7	40.2	22.1	18.6
	8/07	29.1	36.7	43.3	13.4	14.0
	8/10	23.5	14.8	31.6	12.9	13.7
	8/14	15.6	14.8	16.3	23.5	22.3
Middle	7/24	--	--	--	1.7	--
	7/27	--	--	--	1.1	1.1
	7/31	--	--	--	--	--
	8/03	--	--	--	0.3	0.3
	8/07	--	--	--	1.0	1.1
	8/10	0.9	1.1	0.7	0.9	1.4
	8/14	1.0	1.0	1.2	0.8	0.7
Bottom	7/24	--	--	--	1.2	--
	7/27	--	--	--	1.5	1.7
	7/31	--	--	--	--	--
	8/03	--	--	--	0.4	0.3
	8/07	--	--	--	1.0	1.1
	8/10	1.0	1.0	0.8	1.2	1.2
	8/14	1.2	0.9	1.1	0.7	0.8

VOLATILE SOLIDS DISTRIBUTION FOR STUDY 8
(Gas Mixing, 9:1, 0.20, 10% TS Feed)

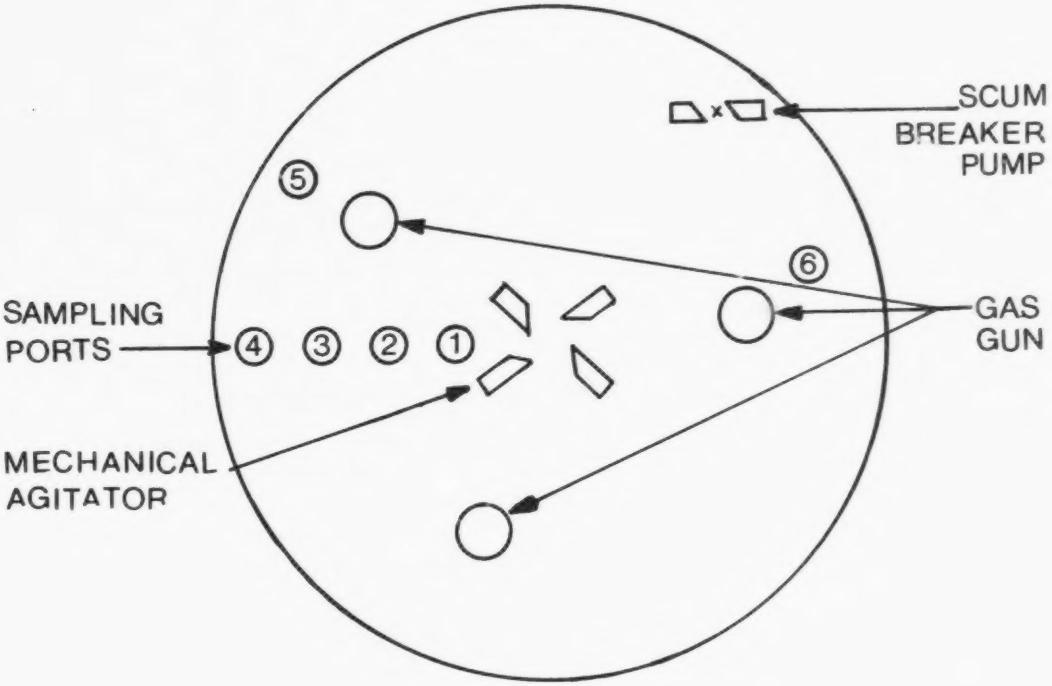
Level	Date	Percent Volatile Solids by Port Number				
		5 (wall)	4	3	2	1 (center)
Top	7/24	61.9	--	--	57.7	--
	7/27	60.4	61.6	51.5	74.8	--
	7/31	59.0	57.3	53.9	70.0	57.5
	8/03	58.8	63.7	58.2	63.2	57.4
	8/07	56.0	52.5	51.7	78.4	74.7
	8/10	69.3	76.8	61.7	73.5	61.5
	8/14	78.4	80.9	78.5	67.4	86.4
Middle	7/24	--	--	--	56.7	--
	7/27	--	--	--	54.7	53.9
	7/31	--	--	--	--	--
	8/03	--	--	--	27.9	27.3
	8/07	--	--	--	48.1	50.7
	8/10	48.3	49.5	46.1	49.3	67.6
	8/14	51.2	50.9	56.0	49.0	49.0
Bottom	7/24	--	--	--	54.0	--
	7/27	--	--	--	54.9	54.7
	7/31	--	--	--	--	--
	8/03	--	--	--	38.4	26.0
	8/07	--	--	--	49.1	49.9
	8/10	53.6	47.6	48.2	50.7	56.8
	8/14	56.3	52.6	54.3	50.2	55.7

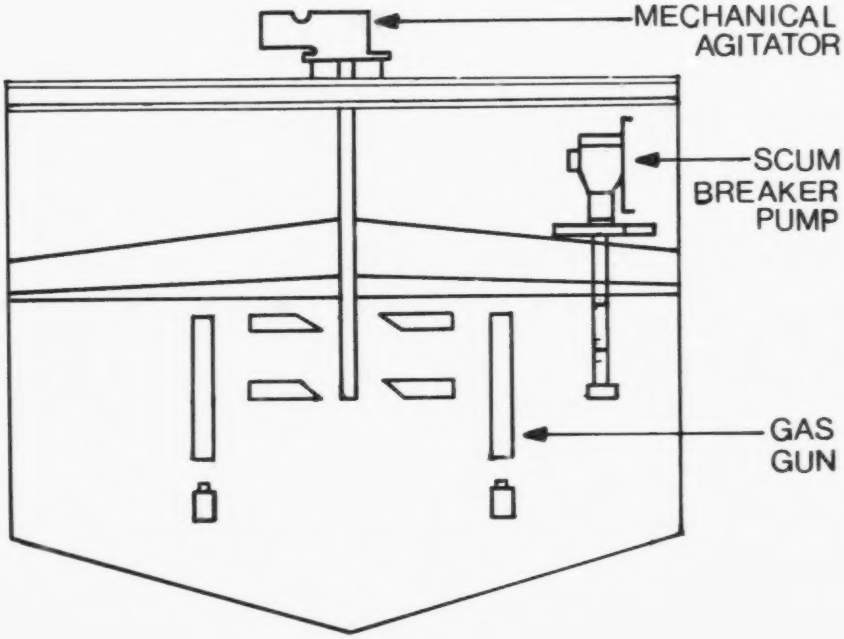
TOTAL SOLIDS DISTRIBUTION FOR STUDY 9
(Mechanical Mixing, 9:1, 0.20, 10% TS Feed)

Level	Date	Percent Total Solids by Port Number 5 (wall)	4	3	2	1 (center)
Top	8/17	22.6	14.5	15.7	16.9	22.0
	8/21	31.7	18.4	12.9	16.5	15.1
	8/24	26.6	24.2	15.5	20.0	13.5
	8/28	18.3	31.4	37.1	15.7	--
	8/31	25.9	20.1	24.2	0.6	0.9
	9/04	21.5	18.5	16.9	0.9	0.8
	9/07	15.6	17.5	14.2	10.2	1.1
	9/11	30.2	28.8	37.0	37.7	1.5
	9/14	19.8	22.9	13.8	31.3	1.3
Middle	8/17	0.7	1.5	0.5	0.4	0.5
	8/21	0.8	0.8	1.0	0.8	0.8
	8/24	0.4	0.9	0.7	0.7	0.8
	8/28	2.6	1.2	0.6	0.6	0.9
	8/31	1.7	2.3	1.2	0.2	0.9
	9/04	2.3	0.6	1.1	0.7	0.8
	9/07	1.9	1.4	1.2	1.2	1.0
	9/11	1.5	1.5	1.2	2.7	1.2
	9/14	1.3	2.0	1.2	1.2	1.0
Bottom	8/17	0.7	0.4	0.8	0.7	0.6
	8/21	0.8	1.0	1.0	1.3	0.9
	8/24	1.2	0.9	0.8	1.0	1.5
	8/28	2.2	1.1	1.2	1.5	2.1
	8/31	1.5	1.5	1.5	1.1	1.2
	9/04	1.2	1.7	1.3	1.1	0.3
	9/07	1.5	1.3	--	1.2	--
	9/11	1.5	1.7	0.9	1.7	1.3
	9/14	1.6	1.7	1.6	1.9	1.0

VOLATILE SOLIDS DISTRIBUTION FOR STUDY 9
(Mechanical Mixing, 9:1, 0.20, 10% TS Feed)

Level	Date	Percent Volatile Solids by Port Number				
		5 (wall)	4	3	2	1 (center)
Top	8/17	89.8	82.6	80.7	74.5	80.7
	8/21	85.0	72.1	73.3	62.6	56.5
	8/24	88.9	75.5	89.2	--	69.0
	8/28	79.5	86.9	64.7	73.9	--
	8/31	83.6	72.8	61.2	43.6	51.7
	9/04	83.8	75.0	72.9	--	57.7
	9/07	85.1	78.4	74.4	70.9	60.0
	9/11	64.7	61.2	63.0	63.9	58.3
	9/14	77.9	78.1	73.7	67.7	55.2
Middle	8/17	48.0	56.0	39.7	35.0	38.2
	8/21	54.3	53.6	61.7	43.8	59.0
	8/24	48.0	52.5	48.6	50.3	51.1
	8/28	63.4	51.3	47.6	46.5	48.0
	8/31	55.6	57.8	83.0	65.1	45.4
	9/04	63.8	21.4	44.8	37.5	45.5
	9/07	64.7	53.8	65.0	55.6	71.4
	9/11	55.3	51.4	55.6	56.4	45.0
	9/14	55.2	55.8	44.4	50.0	52.6
Bottom	8/17	54.3	43.3	49.2	--	21.2
	8/21	51.5	56.7	54.5	48.2	55.7
	8/24	69.3	36.9	33.4	53.4	56.4
	8/28	62.3	53.8	56.3	50.8	55.3
	8/31	54.3	50.9	53.6	46.1	46.2
	9/04	44.0	85.3	47.1	18.5	41.7
	9/07	58.6	69.0	--	57.1	--
	9/11	53.3	58.5	54.2	63.9	43.9
	9/14	52.4	50.0	52.9	52.8	47.6


SCUM BREAKER PUMP
⑤
⑥
SAMPLING PORTS
④ ③ ② ①
GAS GUN
MECHANICAL AGITATOR


MECHANICAL AGITATOR
SCUM BREAKER PUMP
GAS GUN

LIST OF ATTENDANTS

Abeles, Tom
11th Ave., South
Minneapolis, MN 55407

Absher, Susan M.
Environmental Protection Agency
4601 N. Park Ave., #1818
Chevy Chase, MD 20015

Albrecht, Oscar
SHWRD - MERL
26 W. St. Clair St.
Cincinnati, OH 45268

Alter, Harvey
Natl.Ctr.for Resource Recovery
1211 Connecticut Ave., NW
Washington, DC 20036

Ammons, James T.
U.S. Army Corp of Engineers
110 Robin Lane
Huntsville, AL 35802

Anderson, Bernard F.
E.I. DuPont Co.
1610 E. Lafayette Dr.
West Chester, PA 19380

Anderson, Robert C.
Environmental Law Inst.
1346 Connecticut Ave., N.W.
Washington, DC 20036

Anderson, Robert J.
Mathtech
Box 2392
Princeton, NJ 08540

Anderson, Sonia
22 Fairway Dr.
Cranbury, NJ 08512

Arlotta, Salvatore
Wehran Engineering
666 E. Main St.
Middletown, NY 10940

Barineau, James M.
Leon Cty. Public Works
Rt. 2, Box 656
Tallahassee, FL 32301

Basinger, Spencer K.
Oconee Area Plan. & Dev. Comm.
P.O. Box 707
Milledgeville, GA 31061

Beck, Richard B.
Burns & McDonnell Engr. Co.
7821 E. 80th St.
Kansas City, MO 64106

Beck, William W.
A.W. Martin Assoc.,Inc.
900 W. Valley Forge Rd.
King-Prussia, PA 19406

Bernheisel, J. F.
Natl. Ctr. for Resource Recovery
1211 Connecticut Ave., N.W.
Washington, DC 20036

Blackham, William H.
11738 N.W. 26th St.
Coral Springs, FL 33065

Bnjafield, D. W.
Redland Purle Lmt.
Claydons Lane
Essex, England

Bolton, Roger E.
Williams College
Dept. of Economics
Williamstown, MA 01267

Boretsky, Metodij
U.S. Navy
8302 MacArthur Rd.
Wyndmoor, PA 19118

Bromley, John
Waste Research Unit
132 No. Ave.
Abingdon, OXON

Brunner, Dirk R.
Environmental Protection Agency
5491 Wasigo Dr.
Cincinnati, OH 45230

Brunner, Donald E.
U.S. Navy Civil Engr. Lab.
7266 Briarcliff Cir.
Ventura, CA 93003

Buivid, Michael G.
Dynatech Corp.
34 Bowker St.
Brookline, MA 02146

Bush, Harvey H.
Greenleaf/Telesca
1451 Brickell Ave.
Miami, FL 33134

Carpenter, Charles D.
City of Orlando
1046 W. Gore
Orlando, FL 32805

Carroll, William D.
City of Winnipeg
280 William Ave.
Winnipeg, Manitoba Canada

Charbonnier, James W.
American Resource Recovery
P.O. Box 698
Jupiter, FL 33458

Chatterjee, Anil K.
SRI International
333 Ravonswood Ave.
Menlo Park, CA 94025

Checca, Thomas J.
Post,Buckley,Schuh & Jernigan
13420 SW 77th Ave.
Miami, FL 33156

Chian, Edward S.K.
Georgia Tech
Daniel Lab.
Atlanta, GA 30332

Clark, Dave
New Castle Cty.Public Works
2701 Capital Trail
Newark, DE 19711

Clark, Thomas P.
Minn. Pollution Control Agency
3572 Golfview Dr.
St. Paul, MN 55110

Cleveland, Elmer G.
Environmental Protection Agency
345 Courtland St., NE
Atlanta, GA 30308

Cohen, Alan S.
Argonne National Lab.
1543 N. Chickasaw Dr.
Naperville, IL 60540

Cooley, Kevin J.
Post,Buckley,Schuh & Jernigan
3191 Maguire Blvd.
Orlando, FL 32803

Cowhey, James J.
Land & Lakes Co.
123 N. Northwest Highway
Park Ridge, IL 60068

Cresap, C. C.
Dougharty Cty. Public Works
P.O. Box 1827
Albany, GA 31702

Croke, Kevin
2639 Praire
Evanston, IL 60202

Cunningham, Richard D.
The BF Goodrich Co.
500 So. Main St.
Akron, OH 44318

Curtis, Curtis D.
City of Orlando
1046 W. Gore
Orlando, FL 32805

Dahl, Thomas E.
Martel Labs., Inc.
851 Snell Isle Blvd., NE
St.Petersburg, FL 33704

Daly, Ernest
University of Miami
Dept. Mech. Engr.
Coral Gables, FL 33124

Davis, Jack E.
Tuscaloosa Testing Lab.Inc.
P.O. Box 1094
Tuscaloosa, AL 35401

Davis, Robert
189 Sheridan Ave.
Longwood, FL 32750

Deamud, John W.
Reynolds, Smith, Hills
7120 Lake Ellenor Dr.
Orlando, FL 32809

Del Fino, Ronald T.
R.I. Solid Waste Mgmt.
39 Pike St.
Providence, RI 02903

DeLuca, Frank
Rt. 3, Box 1954
Odessa, FL 33556

DeWalle, Foppe
Univ. of Washington
Dept. of Environ. Health
Seattle, Washington 98195

Dietz, Jess C.
Clark,Dietz Engrs.,Inc.
P.O. Drawer 1976
Sanford, FL 32771

Doggett, Ralph
Intl. Research & Tech.
7655 Old Springhouse Rd.
McClean, VA 22101

Domalski, Eugene
307 Summit Hall Rd.
Gaithersburg, MD 20760

Donnelly, Jean A.
Univ. of Cincinnati
2323 Kenlee Dr.
Cincinnati, OH 45230

Dower, Roger
Environmental Law Inst.
1346 Connecticut Ave.,N.W.
Washington, DC 20036

Duggan, James C.
Tennessee Valley Authority
440 Commerce Union Bank Bldg.
Chattanooga, TN 37401

Eacott, Robert B.
Govt. of Western Australia
27 Eaton Villa Place
San Carlos, CA 94070

Eden, Burton H.
Combustion Equip. Assoc., Inc.
61 Taylor Reed Place
Stamford, CT 06906

Elstrom, Alden
271½ Pondella Rd.
N.Ft.Myers, FL 33903

Emrich, Grover H.
A.W. Martin Assoc.,Inc.
900 W. Valley Forge Rd.
King-Prussia, PA 19406

Farrell, Robert S.
ME Dept. of Environ. Protection
Div. of Solid Waste
Augusta, ME 04330

Fenton, Richard
P.O. Box 2842
St.Petersburg, FL 33731

Fiedler, Harry H.
Gilbert/Commonwealth
1615 Hampden Blvd.
Reading, PA 19604

Fillip, Alan J.
Vermont Environment Agency
Maplewood Rd.
E. Montpelier, VT 05651

Fisher, Gerald E.
E.I. DuPont
3707 Chevy Chase
Louisville, KY 40218

Fitzgerald, Sidney S.
SCA Services
901 Silver Hill Rd.
N.Little Rock, AR 72118

Flatt, George
2008 Gibbs Dr.
Tallahassee, FL 32306

Flower, Franklin B.
Cook College-Rutgers Univ.
P.O. Box 231
New Brunswick, NJ 08903

Flynn, Daniel V.
Ill. Environ. Protection Agency
603 Eastman Ave.
Springfield, IL 62702

Fowler, Bert
Waste Mgmt. of Ill.
P.O. Box 563
Palos Hgts., IL 60463

Francingues, Norman
100 Redbud Dr.
Vicksburg, MS 39567

Franklin, William E.
Franklin Assoc., Ltd.
8340 Mission Rd., Suite 101
Prairie Vill., KS 66206

Freeman, Harry
IERL - EPA
Cincinnati, OH 45268

Friedman, D.
Environmental Protection Agency
401 M Street S.W.
Washington, DC 20460

Fuller, Wallace H.
Univ. of Arizona
Soils, Water & Engr.
Tucson, AZ 85721

Gabbay, S. M.
Occidental Research Corp.
P.O. Box 19601
Irving, CA 92713

Gangopadhyay, Tota
Beasy Nicoll Engr.Ltd.
6080 Young St., Suite 512
Halfiax, Nova Scotia

Garmon, Ronald C.
Texaco Inc.
3600 Normandy, Apt. A-9
Port Arthur, TX 77640

Garrity, Richard D.
City of Tampa
City Hall Plaza
Tampa, FL 33803

Geswein, Allen
401 M. Street, SW
Washington, DC 20460

Giddings, Todd
Todd Giddings & Assoc.
140 W. Fiarmount Ave.
State College, PA 16801

Goodson, Robert H.
Seaburn & Robertson, Inc.
5510 Gray St., Suite 118
Tampa, FL 33609

Gorczynski, Jan
Stevens Elastomeric Prod.
25 Payson Ave.
Easthampton, MA 01027

Gordon, Judith G.
The Mitre Corp.
1448 Aldenham Lane
Reston, VA 22090

Gresh, Gerald
3162 N.E. 7th Dr.
Boca Raton, FL 33431

Griffin, Robert A.
Ill. St. Geological Survey
609 W. Columbia
Champaign, IL 61820

Griffith, Lloyd W.
Ross Saarinen Bolton & Wilder
200 E. Robinson St.
Orlando, FL 32801

Gupta, Ashok
Raytheon Service Co.
2 Wayside Rd.
Burlington, MA 01730

Haigh, C. C.
Beaufort Cty. Public Works
P.O. Box 4279
Beaufort, SC 29902

Halvorson, Thomas G.
Union Carbide Corp.
5535 Mapleton Rd.
Lockport, NY 14094

Ham, Robert
2130 Chadbourne Ave.
Madison, WI 53705

Hanna, Edward E.
City of Orlando
1046 W. Gore
Orlando, FL 32805

Hansen, Warren G.
SCS Engineers
2875 152nd Ave., NE
Redmond, WA 98052

Harp, James D.
Senergy, Inc.
2961 Fitzooth Dr.
Winter Park, FL 32792

Hartz, Ken
702 G Eagle Hts.
Madison, WI 53705

Hasselriis, Floyd
Combustion Equip.
555 Madison Ave.
New York, NY 10022

Haxo, Henry E.
Matrecon Inc.
Box 24075
Oakland, CA 94623

Hecht, Norman L.
Univ. of Dayton Research Inst.
300 College Park Dr.
Dayton, OH 45469

Heckler, Dave
Thomas,Dean & Hoskins,Inc.
3808 8th Ave., So.
Great Falls, MT 59405

Helmstetter, Arthur J.
Systems Tech. Corp.
245 North Valley Rd.
Xenia, OH 45385

Hendrix, Sylvan
Koppers-Sprout Waldron Div.
P.O. Box 6221
Lakeland, FL 33803

Hentrick, Robert
Systems Tech. Corp.
245 No. Valley Rd.
Xenia, OH 45385

Heyden, Peter
Cahn Engineering
Alex Dr.
Wallingford, CT 06904

Hickey, Peter
New Executive Office Bldg.
Room 3011
Washington, DC 20024

Hill, David T.
Auburn University
1817 SW 78th Terrace
Gainesville, FL 32601

Hoye, Robert
Pedco Environmental, Inc.
11499 Chester Rd.
Cincinnati, OH 45246

Hudson, James F.
Urban Systems Research
36 Boylston St.
Cambridge, MA 02138

Hunt, Robert G.
Franklin Assoc., Ltd.
8340 Mission Rd.
Prairie Vill., KS 66206

Hunt, Tim F.
P.B.Co.Solid Waste Authority
120 So. Olive Ave.
West Palm Bch, FL 33401

Husain, Mohammad A.
FL Dept. of Environ. Reg.
1409 Chowkeebin Lane
Tallahassee, FL 32301

Iglehart, Cecil
SCA Services, Inc.
8806 Nottingham Pkwy.
Louisville, KY 40222

James, Steve
SHWRD - MERL
26 W. St. Clair St.
Cincinnati, OH 45268

Jones, Larry W.
U.S. Army Corp of Engineers
Univ. of Tenn.
Knoxville, TN 37916

Kinman, Riely N.
Univ. of Cincinnati
415 Stevenson Rd.
Erlanger, KY 42028

Kirklin, Duane R.
Natl. Bureau of Standards
Chem/B348
Washington, DC 20234

Klee, Albert
SHWRD - MERL
26 W. St. Clair St.
Cincinnati, OH 45268

Klein, Michael S.
Mgmt. of Res. & Environ.
41C New London Turnpike
Glastonbury, CT 06033

Knight, James A.
Georgia Inst. of Tech.
2117 Kodiak Dr. NE
Atlanta, GA 30345

Laden, Kenneth G.
Dept. of Envir. Services
1321 So.Carolina Ave.,SE #4
Washington, DC 20003

Landreth, Robert E.
Environmental Protection Agency
26 West St. Clair
Cincinnati, OH 45268

Lavigne, Ronald L.
Resource Control Inc.
Quabbin Office Bldg.,Valley Rd.
Barre, MA 01115

Layland, Dwane
Lycoming Co.
48 W. Third St.
Williamsburg, PA 17701

Lazarus, Arthur G.
C-E Maguire, Inc.
31 Canal St.
Providence, RI 02903

LaZenby, Mack R.
City of Sanford
P.O. Box 1778
Sanford, FL 32771

Leamon, Michael R.
Forsyth Cty. Eniron. Dept.
2150 Storm Canyon Rd.
Winston-Salem, NC 27106

LeCroy, Charles E.
Bay Cty. Solid Waste Dept.
206 South 22 A
Panama City, FL 32401

Lewis, David
York Research Corp.
1 Research Dr.
Stanford, CT 06906

Lincoln, Edward
University of Florida
AG. Engr. Dept.
Gainesville, FL 32611

Liskowitz, John W.
NJ Inst. of Tech.
Bunker Dr., RD #2
Belle Mead, NJ 08502

Lopez, Ralph A.
Mayes, Sudderth & Etheredge
5750 Major Blvd.
Orlando, FL 32805

Love, John
Univ. of Mo.-Columbia
Engr. Bldg. 2024
Columbia, MO 65201

Loven, Carl
Jamestown Star Rt.
Peakview Dr.
Boulder, CO 80302

Lowe, Grady
City of Lake Worth
1301 12th Ave. So.
Lake Worth, FL 33460

Lutton, Richard
U.S. Army Corp of Engineers
P.O. Box 631
Vicksburg, MS 39180

MacDaniel, Robert D.
California Pellet Mill Co.
1450 Kleppe Ln.
Sparks, NV 89431

Malone, Philip G.
U.S. Army Corp of Engineers
P.O. Box 631
Vicksburg, MS 39180

Mather, Thomas W.
Tim Mather, Inc.
2701 Casey Key Rd.
Nokomis, FL 33555

Mavinic, Donald S.
Univ. of British Columbia
1001 Canyon Blvd.
N.Vancouver, B.C.,Canada V7R2K2

Mayo, Franics T.
Environmental Protection Agency
26 West St. Clair St.
Cincinnati, OH 45268

Mc Dermont, Donald
Post,Buckley,Schuh,& Jernigan
7500 N.W. 52nd St.
Maimi, FL 33166

Mc Guire, Jerry N.
Monsanto Company
800 N. Linberg Blvd.
St. Louis, MO 63166

McConnell, Wayne
15257 E. Colonial Dr.
Oralndo, FL 32809

McGregor, K.
Mgmt.Resources & Environ.
41C New London Turnpike
Glastonbury, CT 06033

McManamy, John
250 Carib Dr.
Merritt Isle., FL 32952

Mellott, Philip K.
Nishna Sanitary Serv.,Inc.
P.O. Box 182
Elliott, IA 51532

Meyer, G. L.
USEPA
Ofc. Radiation Progs.
Washington, DC 20467

Miller, Carlton K.
Broward County
Room 526, 236 S.E. 1st Ave.
Ft.Lauderdale, FL 33301

Mitchell, Gary L.
SCS Engineers
11800 Sunrise Valley Dr.
Reston, VA 22091

Mitchell, John W.
Franklin Assoc.,Ltd.
8340 Mission Rd.
Prairie Vill., KS 66206

Montgomery, Dale
Versar, Inc.
3257 Victor Cir.
Annadale, VA 22003

Mooij, Hans
Environ. Impact Control Dir.
Fisheries & Environ. Canada
Ottawa, Ontario, Canada

Moore, Byron G.
City Of Orlando - Public Service
400 W. Livingston St.
Orlando, FL 32802

Moreau, Raymond L.
FL Res. Recovery Council
2600 Blair Stone Rd.
Tallahassee, FL 32301

Morgan, William L.
Board of Health
308 N. 16th St.
New Castle, IN 47362

Murray, David E.
Reitz & Jens, Inc.
111 S. Meramec
St. Louis, MO 63105

Mutch, Robert D.
Wehran Engineering
666 E. Main St.
Middletown, NY 10940

Myers, Tommy
Waterways Experiment Station
P.O. Box 631
Vicksburg, MS 39180

Neff, Russell R.
Mayes, Sudderth & Ethredge
5750 Mahor Blvd., Suite 200
Orlando, Fl 32805

Neisser, Mark
John G. Reutter Associates
9th & Cooper Streets
Camden, NJ 08101

Nichols, Walter P.
State Of Alabama - Public Health
State Office Building
Montgomery, AL 36130

Noble, David
4827 W. Bradock
Alexandria, VA 22311

Nollet, Anthony R.
AENCO Inc.
Box 387
New Castle, DE 19720

Oberacker, Don
SHWRD - MERL
26 W. St. Clair St.
Cincinnati, OH 45268

Oppelt, Edwin T.
Environmental Protection Agency
7939 Shelldale Way
Cincinnati, OH 45242

Pace, Robert
1291 Plymouth Place
Jacksonville, FL 32205

Patel, Vijay
Pedco Enviornmental, Inc.
11499 Chester Rd.
Cincinnati, OH 45246

Peritz, Leigh A.
Raytheon Service Co.
63 Washington St.
Winchester, MA 01890

Peterson, Arnold
Stevens Elastomeric
26 Payson Ave.
Easthampton, MA 01027

Pohland, Fred
Georgia Tech - Civil Engineering
4631 North Springs Ct. NE
Atlanta, GA 30338

Polk, Malcolm
Atlanta University
Dept. of Chemistry
Atlanta, GA 30314

Power, Richard M.
SCA Services, Inc.
19 Daley Ave.
Methuen, MA 01844

Pullan, Henry
Redland Purle Lmt.
Claydons Lane
Essex, England

Purdy, Kenneth R.
Tech Consultants, Inc.
1485 Leafmore Ridge
Decatur, GA 30033

Rebholz, Richard P.
City of Fort Walton Beach
Rt.1, Box 91
Mary Esther, FL 32569

Reese, John A.
FL Dept. of Environ. Reg.
2600 Blairstone Rd.
Tallahassee, FL 32301

Reilly, Bertram
9 Choctaw Trail
Ormond Beach, FL 32074

Reynolds, Stan L.
Syst.,Science & Software
Box 1620
La Jolla, CA 92038

Rinaldo, Marjory L.
Residuals Mgmt. Tech.
1406 E. Washington Ave.
Madison, WI 53703

Ritchie, Charles W.
Dept. for Natural Resources
209 Pin Oak Place
Frankfort, KY 40601

Robbins, John A.
Sverdrup & Parcel & Assoc.
174 Royal Palm St.
Sebastian, FL 32958

Roberson, David L.
State Public Health
State Office Bldg.
Montgomery, AL 36130

Rogers, Charles J.
Environmental Protection Agency
461 Merry Maid Lane
Cincinnati, OH 45240

Roulier, Mike
SHWRD - MERL
26 W. St. Clair St.
Cincinnati, OH 45268

Rugg, Barry
New York Univ.
Barney Bldg.
New York, NY 10003

Sanning, Don
SHWRD - MERL
26 W. St. Clair St.
Cincinnati, OH 45268

Sarver, Glen E.
B.F. Goodrich Co.
Rt. 3, Box 11
Marietta, OH 45750

Scaramelli, Alfred B.
Mitre Corp.
4 Carley Rd.
Lexington, MA 02173

Scarpino, P. V.
Univ. of Cincinnati
Dept. of Civil & Env. Engr.
Cincinnati, OH 45221

Schmoeger, Gary A.
Martel Labs.,Inc.
6231 Cedar St.,NE
St.Petersburg, FL 33702

Schnelle, James F.
C-E Maguire, Inc.
31 Canal St.
Providence, RI 02903

Schomaker, Norbert B.
Environmental Protection Agency
65 Bayham Dr.
Cincinnati, OH 45218

Searcy, Phillip E.
Post,Buckley,Schuh & Jernigan
3191 Maguire Blvd.
Orlando, FL 32803

Seelinger, Richard W.
VOP, Inc.
40 VOP Plaza
Des Plaines, IL 60016

Sengupta, Subrata
University of Miami
Dept. Mech. Engr.
Coral Gables, FL 33124

Shanks, Howard R.
Ames Laboratory
A207 Phys. Bldg.
Ames, IA 50011

Silva, Thomas F.
General Electric
782 Downing St.
Schenectady, NY 12309

Simister, Bruce W.
Midwest Research Inst.
4135 N.E. Davidson Rd. #374
Kansas City, MO 64116

Simpson, William P.
Post,Buckley,Schuh & Jernigan
3191 Maguire Blvd.
Orlando, FL 32803

Skinner, John
US EPA (AW 5-64)
401 M St., SW
Washington, DC 20460

Smith, Douglas F.
Dept. Environ. Reg.
825 NW 23rd. Ave., Suite G
Gainesville, FL 32601

Smith, Frank M.
Leon County
Rt. 2, Box 656
Tallahassee, FL 32301

Smith, Mark E.
Residuals Mgmt. Tech.
4201 Winnequah Rd.
Monona, WI 53716

Srinivasan, V. R.
Louisiana State University
Baton Rouge, LO 70803

Steeves, W. M.
Reynolds,Smith & Hills
P.O. Box 4850
Jacksonville, FL 32201

Stenburg, Robert L.
Environmental Protection Agency
26 W. St. Clair St.
Cincinnati, OH 45268

Stenstrom, Michael K.
Univ. of California, L.A.
7619 Boelter Hall, UCLA
Los Angeles, CA 90024

Steven, Theodore
Alex Dr.
Wallingford, CT 06904

Stoffel, Clarence M.
Owen Ayres & Assoc.
Rt. 3, Box 16B
Bloomer, WI 54724

Stoll, Bernard J.
USEPA, OSW
401 M St., SW
Washington, DC 20460

Surowiec, Joseph T.
State of Georgia
3454 Alison Dr.
Doraville, GA 30340

Sussman, David
907 6th St.,SW,605-C
Washington, DC 20024

Swartzbaugh, Joseph T.
Systems Tech. Corp.
245 No. Valley Rd.
Xenia, OH 45385

Taylor, James
University of Central Fla.
P.O. Box 25000
Orlando, FL 32816

Teer, Ellis H.
Glace & Radcliffe, Inc.
1347 Palmetto Ave.
Winter Park, FL 32789

Terrill, David
Lycoming Co.
48 W. Third St.
Williamsburg, PA 17701

Thomas, Robert A.
Southwest Ga. APDC
P.O. Box 346
Camilla, GA 31730

Trezek, George
CA Recovery Systems, Inc.
160 Broadway, Suite 200
Richmond, CA 94804

Underwood, George T.
Underwood & Assoc.
Ft. Myers, FL 33904

Vandervort, John D.
Schlegel Area Sealing Syst.
54 Aldwick Rise
Fairport, NY 14450

Vesilind, P. A.
Duke University
Dept. of Civil Engr.
Durham, NC 27706

Wagner, Paul L.
Mayes,Sudderth & Etheredge
3370 Vandiver Dr.
Marietta, GA 30066

Walsh, James J.
SCS Engineers
5242 Camelot Dr.
Fairfield, OH 45014

Walter, Donald K.
Dept. of Energy
20 MS 2221C
Washington, DC 20545

Wanielista, Martin P.
University of Central Fla.
P.O. Box 25000
Orlando, FL 32816

Ward, George D.
George D. Ward & Assoc.
821 NW Flanders
Portland, OR 97209

Watson, Jack E.
Seaman Corp.
401 Freeman Hill
Tryon, NC 28782

Weaver, Larry D.
Warner Robins Air Log.Ctr.
113 Glenn Dr.
Warner Robins, GA 31093

Weinberger, Carl S.
Teledyne National
1910 Pot Spring Rd.
Timonium, MD 21093

Weinstein, Jack S.
Mayes,Sudderth & Etheredge
5750 Major Blvd.,Suite 200
Orlando, FL 32805

Welch, Jerome
Kansas Geol. Survey
2606 Bonanza St.
Lawrence, KS 66044

Wheeler, William B.
NE Georgia Planning Comm.
115 Lavender Rd.
Athens, GA 30606

White, Robert
425 Volker Blvd.
Kansas City, MO 64110

Wigh, Richard J.
Regional Services Corp.
3320 Woodcrest Ct.
Columbus, IN 47201

Wiles, Carlton C.
Environmental Protection Agency
5853 Brasher Ave.
Cincinnati, OH 45242

Wilkey, Michael L.
Argonne Natl. Lab.
9700 S. Cass Ave.
Argonne, IL 60439

Willey, Cliff R.
MD Environ. Service
60 West St.
Annapolis, MD 21403

Wilson, Frank L.
Polk Cty. Environ. Services
P.O. Box 39
Bartow, FL 33830

Wilson, Ronald H.
Stottler Stagg & Assoc.
P.O. Box 272
Winter Haven, FL 33880

Woelfel, Gregory C.
Waste Management, Inc.
900 Jorie Blvd.
Oak Brook, IL 60521

Wong, Kau-Fui
University of Miami
Dept. Mech. Engr.
Coral Gables, FL 33124

Wood, G. M.
Ontario-Environment
135 St. Clair Ave., W.
Toronto, Ontario Canada

Worrell, William A.
Brown & Caldwell
53 Perimeter Ctr. East
Atlanta, GA 30346

Young, Richard M.
Kansas Geological Survey
2503 Winterbrook Dr.
Lawrence, KS 66044

Yousef, Yousef A.
University of Central Fla.
P.O. Box 25000
Orlando, FL 32816

Zenzel, Kenneth M.
Senergy, Inc.
433 Oak Haven Dr.
Altamonte Spr, FL 32701

Zimmerman, R. E.
Escor, Inc.
820 Davis St.
Evanston, IL 60201

Zumwalt, John B.
Post,Buckley,Schuh & Jernigan
2131 Hollywood Blvd.
Hollywood, FL 33020

Zwolak, Richard A.
Hillsborough Cty.
700 Twiggs St., Suite 800
Tampa, FL 33612